REPORT

Underground Solutions for Urban Waste Management: Status and Perspectives

January 2013

ISWA – the International Solid Waste Association
is a global, independent and non-profit making association, working in the public interest to promote and develop sustainable and professional waste management worldwide

Prepared by the Task Force Globalisation

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Foreword

This report has been prepared as part of the work of the ISWA Task Force on Globalisation and Waste Management within the frame of megacities, globalisation and waste management. The Task Force aims inter alia to promote and raise awareness of the new challenges that globalisation has placed on waste management practices and planning in the context of urban areas and megacities.

Underground Solutions for Urban Waste Management

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Executive Summary

Introduction

The utilization of subsurface space is nowadays a key issue towards attaining an environmental friendly and sustainable development, especially in urban areas. Thus, activities or infrastructures that are difficult, impossible, environmentally undesirable or even less profitable to be installed above ground can be relocated underground releasing valuable surface space for other uses and enhancing urban living conditions.

Hence, the management of waste through underground developed infrastructure can be looked as an important evolution which would allow for the efficient and cost-effective tackling of one of the more pressing needs of modern society. This report aims at presenting the solutions offered by such infrastructure, at identifying their operational characteristics and specific advantages as well as at providing insight regarding their cost data, benchmarked against traditional management schemes. Furthermore, through selected case studies the applicability of such schemes and the decision process that led to their adoption is analyzed. Finally, future issues which can further enhance the efficiency of the underground waste management schemes are identified and analyzed.

Urbanization and waste generation

Today, the total waste generated worldwide in an annual basis amount to more than 4 billion tons. Almost 45% of these are considered as municipal solid waste, while the rest is industrial waste, including hazardous one.

The daily waste production per capita ranges from 0.6 kg to 1.4 kg, with people in highly developed countries producing more waste. In the coming years, both the increase of global population and the growth or GDP per capita in developing countries is expected to create a boost in the global municipal waste production. Only for the case of urban food waste it has been estimated that between 2005 and 2025 its generation will increase by around 45%.

Underground waste collection systems

Rising waste volumes, increased hygienic and amenity demands as well as environmental considerations impose additional requirements to the waste management system that traditional management schemes are either unable to meet or come across with increased operating cost figures. The utilization of the subsurface space can provide the setting for the development of infrastructure which is capable of addressing in a more efficient manner the limitations of existing waste management schemes. Thus, following the example already set by other utilities (e.g. water, sewerage, gas, electricity, etc.) that have developed over time into an underground infrastructure grid, it is expected that the management of various waste streams through underground infrastructure will grow rapidly.

The underground systems can either operate as stand-alone collection points or can incorporate automated vacuum collection schemes (AVAC or Automatic Solid Waste Collection system - AWCS), in which the waste are pneumatically transported to a centralized facility for further process. Both systems can manage different waste streams (e.g. mixed waste, paper, etc.) with the inclusion of additional collection points or inlets.

Stand alone underground containers

The first category, namely the stand-alone collection follows a more traditional approach, where waste containers are replaced by underground collection points. These points have their greater portion placed underground, having only their inlets above ground surface. Stand-alone underground or semi-underground collection points offer great advantages over traditional collection bins, as:

- greater holding capacity than of the same area's surface dumpsters/bins
- compaction of the waste, increasing their effective capacity by 1.5 to 2.5 times
- improved aesthetics
- high hygienic standards, controlling bacterial development and odor problems
- limited maintenance requirements and superior protection against vandalism

The above features can allow for a considerable increase in the collection interval that can lead to the reduction of the operating cost (transportation, labor, etc.) of the service, ranging from 5% to 30%. Furthermore, the minimal capital expenditure required as well as the flexibility in its siting requirements make such systems ideal for the instant replacement of the wheel containers. Especially for the case of the developing countries, the implementation of stand-alone underground collection scheme seems to be the most sensible strategy.

Automated vacuum collection systems (AVAC)

Automated vacuum (pneumatic) waste collection systems (AVAC) provide an integrated framework for the tacking of the waste handling problem. Not only do they provide temporal storage but also the transportation of waste is taking place through underground pipeline network to a waste collection terminal. By doing so, AVAC systems provide an attractive alternative to conventional vehicle-operated waste collection, as they offer advantages in terms of reduced traffic-related problems, such as noise, accidents, CO_2 emissions, congestion and improve overall safety and hygienic levels. This speeds up the whole garbage collection process, especially at difficult cases as overcrowded urban centers, allowing at the same time a smooth operation of the system even at difficult situations either as a result of severe weather conditions (e.g. storms) or external events (e.g. strikes, protests, etc.).

Major benefit from the usage of AVAC system is the minimized operating cost for the waste handling; 2 to 3 times lower than conventional collection methods. For example SWECO has estimated that the operating cost of the Västra Sjöstaden development project using AVAC system is approximately 3,5 times lower compared to the manual handling of surface containers. Also in a similar study in UK for the development of a new housing project of 10,000 flats the operating cost using the AVAC scheme is calculated at £21 per flat /year, while the cost of the traditional collection method is around £67 per flat /year.

The drawbacks are related to the initial investment required for the setting up of the system which can be substantially higher (30%-50%) than of a respective surface collection scheme and in the current limitations of the AVAC in handing special waste fractions as cardboard and glass waste as well as WEEE or other bulky waste types. Nevertheless, as indicated in the repost, the reduced operation cost can result to a viable investment scenario, which, in the long run, can counterbalance the negative influence of the high capital expenditure. Furthermore, new technological developments is expected to expand the applicability envelop of the AVAC system in the near future.

Underground hazardous waste repositories

In the case of special and hazardous waste things are even more favorable when assessing the advantages offered by underground repositories. These derive mainly from the fundamental characteristics of underground space; namely the opacity and the natural protection offered, ensuring minimal impacts to the biosphere. Furthermore, when the "on-site" underground disposal is adopted, the benefits from such a solution combine the advantages gained from the underground siting of the repository coupled with the particular opportunities derived by the proximity between the waste producer site and the repository's location.

Future issues to be considered

The trend towards underground waste management solutions can be further strengthened by the development of other systems and strategy options which would allow for a further increase in the efficiency of the underground schemes. These are:

- Utilization of underground freight transportation
- Development of multi-purpose utility tunnels

- Research on energy consumption reduction and on the collection options for special waste fractions
- Intensification of pay-as-you-throw (PAYT) and source separation policies
- Assessment of external cost in financial analysis

The above issues can provide competitive advantages and reveal the true perspectives of underground solutions for urban waste management capitalizing on their comparative advantages; offering zero nuisance in a cost-effective manner.

I. Underground Space Development

1. Introduction – The driving force of going underground

Since the dawn of our civilization humans have always used the subsurface for a variety of purposes. The caves and other underground openings that nature provided, served as man's first habitats. Protection from the natural elements and from attacks was among the main considerations for moving underground and perhaps cave dwellings constitute man's first recorded use of the underground space. During the following stages of human evolution mankind intensively utilized the natural resources of the subsurface with a view to fulfilling the growing needs of our civilization.

It appears as though we have come full circle as today humankind resort again to the underground space for a different reason. The last decades the world has experienced an unprecedented population growth, especially in the urban areas. Urbanization is the term that characterizes this phenomenon and is responsible for the creation of large urban centers. In 2010, 50.6% of the world population lived in urban regions. This means that for the first time in human history, the world's population became more urban than rural. This trend seems irreversible and it is projected that by 2050 urban dwellers will likely account for 86% of the population in the more developed and 67% in the less developed regions. Overall, it is expected that 7 out of 10 people will be living in urban areas by 2050. The data project that in 2050 the total world population will be around 9.5 billion; hence, it is expected that a total of around 6 billion people will reside in urban centers (UN-HABITAT, 2010).

The concentration of many people and human activities in relatively small surface area created the need to expand residential areas in order to fulfill the demands for better living conditions. Cities began to expand "horizontally" or "two dimensionally". The urban sprawl consumed neighboring "green areas", while free surface space was more and more diminishing. The consequences of the uncontrolled city sprawl have created inconsistencies with the sustainable development concept, resulting in the deterioration of the living conditions in urban areas. Stretching the city borders and, therefore, invading the countryside does not solve the problems but only postpones them, making them more acute to tackle (Durmisevic, 1999). It is only lately that urban planners are beginning to realize that there is a resource practically unexploited so far, the underground space. This particular recourse has the potential to alleviate the above-mentioned problems, as it has been proven in several cases, and thus, it can provide new space for the city's development.

2. Underground space – Definition and uses

Underground space refers to a space that is situated below ground level. Surface space is accordingly defined as a space (built or unbuilt) found above ground level, with the latter defined as the natural elevation of the surface of the ground. Underground space can

provide the setting for activities or infrastructures that are difficult, impossible, environmentally undesirable or even less profitable to be installed above ground.
According to Ronka et al. (1998) underground space can be divided into different categories with respect to its end-use:

- general public facilities, such as swimming pools and connectors between subways,
- traffic space and transportation systems, such as mass transit, roadways and parking facilities,
- technical maintenance facilities, such as waste, water and sewerage treatment, power generation and corridors for the utility pipelines and cabling,
- industrial / production facilities, such as temperature controlled storage, storage and logistics warehouses, noisy and dusty processing,
- special use facilities, such as defense and telecommunication facilities.

What is usually observed is a gradual transition of uses to greater development/construction depths in cases where facilities are not accommodating needs of the general public, installations are becoming more complex or when their housed functions are unwelcomed or unwanted in surface areas. This is illustrated in Fig. 1.1 where underground structures are categorized with respect to their end-use and positioned accordingly at their feasible construction levels (Ronka et al., 1998).

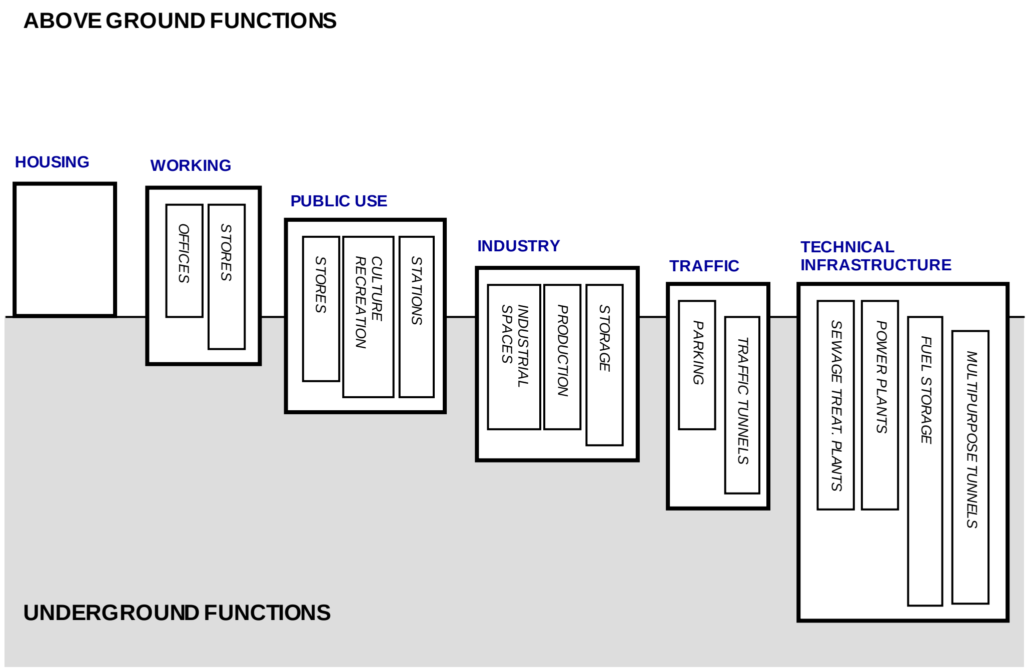


Fig. 1.1. Feasible depths for the development of underground use types in the urban structure (Ronka et al., 1998).

3. Advantages of utilizing the underground space

Among the main advantages of the utilization of underground space are the release of space on the surface, that could be used for recreation / social activities, the development of new green fields and residential areas, the preservation of "sensitive" areas, such as historical city centres and archaeological sites, the reduction of travel distances by the better concentration of functions, as well as considerable energy and time savings.

The development of underground infrastructures would allow for a higher efficiency and availability degree in their use, resulting in a maximum utilisation, having on the same time lower maintenance costs. The utilization of underground space allows a facility to be built in a location where a surface facility is not possible, either because of a lack of surface space or because building a surface facility in that location is not acceptable from the community. Furthermore, some of the infrastructures required in modern cities or even basic functions of the city (e.g. transportation, shopping, theatres, catering facilities, etc.) can be partly transferred toward the underground (Maire et al., 2006).

Underground structures typically provide superior resistance, with respect to above ground structures, to catastrophic events such as earthquakes, hurricanes, tornados, external fires, external blasts, radiation and other terroristic threats. At the same time, the installation of hazardous processes (industrial uses, hazardous waste treatment and disposal, etc.) below ground level ensures minimum risk and disturbances (visual impact, noise pollution, odours, etc.) as the ground medium acts as a barrier structure blocking their mitigation to the aboveground living environment.

Thus, the gains from increasing the use of the underground space can be considerable: more cost-effective use of the infrastructure, better traffic mobility, reduced environmental impacts (noise levels, odor issues, risk threats, etc.), leading to the renewal of cities and especially urban environments, attaining there a considerable improvement of the quality of life (Durmisevic, 1999).

From the above, it is assessed that the choice for the underground development or the underground relocation of a particular infrastructure or use should be considered when:

a. the surface resources required are difficult to find or unavailable,
b. there is a significant economic benefit resulting in the viability of the solution,
c. special protection requirements are enforced and/or the safeguarding of the environmental integrity is of importance.

Furthermore, underground space provides hosting for several non-ordinary types of applications, ranging from high tech laboratories (e.g. Super-Kamiokande neutrino observatory) to urban farm (Pasona O2 subterranean farm), while at the same time giving space for visionary projects utilising existing facilities (e.g. vertical metropolis – Fig. 1.2) or developing new underground urban space projects (e.g. project "Earthscraper").

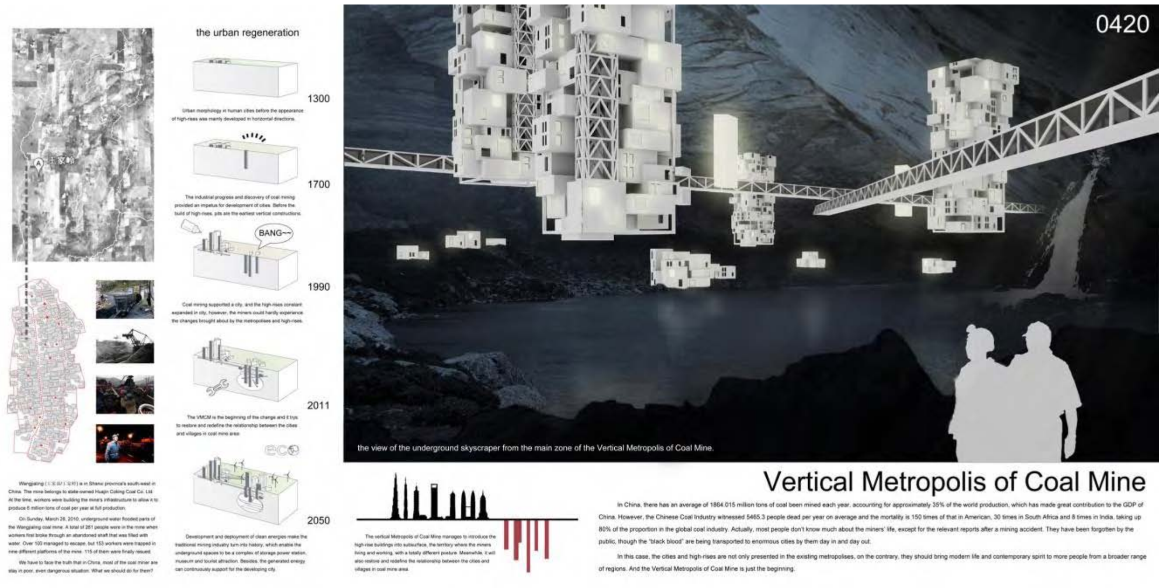


Fig. 1.2. Future vision of an underground metropolis in China (Fan Shuning and Zhang Xin - Finalist 2011 Skyscraper Competition – eVolo magazine).

Nevertheless, to fully take advantage of the strong-points of underground development its integration within the city planning is mandatory. In this manner ITA - International Tunnelling Association has accepted a policy statement that encompasses clear guidelines for the underground land use planning process. It states that "*the subsurface is a resource for future development...and subsurface planning should be an integral part of the normal land use planning process ... national, regional and local policies should be prepared to provide guidelines, criteria and classifications for assessing appropriate uses of underground space, identifying geologic conditions, defining priority uses and resolving potential utilization conflicts*". Such policies are gradually brought into effect, especially in developed countries, and the 3 dimensional planning of the cities is gaining pace.

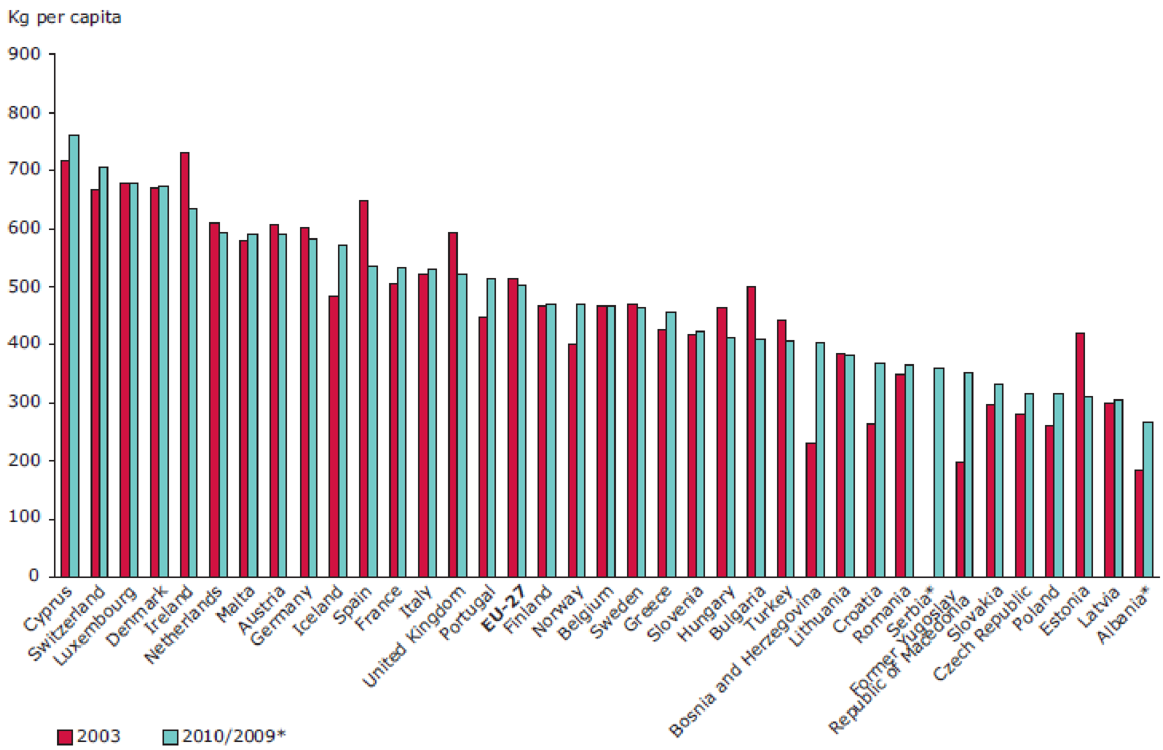
II. Urban Waste and Underground Management Schemes

1. Urban wastes production trends – Brief data

Waste management is one of the major issues of urban engineering. Today, the total amount of waste generated annually worldwide (municipal, industrial, hazardous) is more than 4 billion tons (Veolia, 2009). Almost 45% of these are considered as municipal solid waste, while the rest is industrial waste, including hazardous one.

The EU-27 Member States plus Croatia, Norway and Turkey generated in total some 2.6 billion tonnes of waste in 2008, or roughly 5.4 tonnes per person, of which around 3.7 % is hazardous (EEA, 2012). This was slightly lower than in the years 2004 and 2006 where the EU-27 total amounted to 2.68 billion tonnes and 2.73 billion tonnes respectively. In general, 32% of the waste generated in the EEA countries is from construction and demolition activities, 27% from mining and quarrying, and the rest from manufacturing, households and other activities.

The annual generation of municipal waste, mainly from households but including similar wastes from such sources as commerce, offices and public institutions in the EU-27 has reached 502 kg per person in 2010 (Fig. 2.1).



Source: Eurostat data centre on waste, 2012; ZOI, 2011.

Fig. 2.1. Trend in generation of municipal wastes (kg per capita) in the EU, EFTA countries, Turkey and Western Balkan countries in 2003 and 2010 (EEA, 2012).

In Table 2.1 the production of urban solid waste is presented with respect to the level of the country's development (Cointreau, 2007). The daily waste production per capita ranges from 0.6 kg to 1.4 kg, with people in highly developed countries producing more waste.

Table 2.1. Production of urban solid wastes with respect to the level of country's development (Cointreau, 2007).

	Population	**Municipal waste quantities in urban areas**
High revenue developed countries	1 billion	Approx. 1.4 million tn per day (1.4 kg/capita/day)
Average revenue developing countries	3 billion (approx. 30% of the urban population live in shantytowns)	Approx. 2.4 million tn per day (0.8 kg/capita/day)
Low revenue developing countries	2.4 billion (approx. 65% of the urban population live in shantytowns)	Approx. 1.4 million tn per day (0.6 kg/capita/day)

In the coming years, both the increase of global population and the growth or GDP per capita in developing countries is expected to create a boost in the global municipal waste production. Only for the case of urban food waste it has been estimated that between 2005 and 2025 its production is expected to increase by around 45% (Mavropoulos, 2010). Thus, urban population will be facing new challenges to efficient address the management of urban solid waste.

This increase is also expected to happen in the urban waste-water requiring proper treatment. Nowadays, waste-water from households and different industries represent a significant pressure on the environment and treatment is normally required before discharge. A domestic household produces an average of 200–300 lt of wastewater per person per day.

Things are more positive in developed countries where collection systems and treatment plants cover the majority of the population. For example, in EU member states are required to comply with Directive 91/271/EEC (Urban Waste Water Directive) which mandates that by the 31th of December 2005 all EU countries were required to provide collecting and treatment systems in all agglomerations with a population equivalent (PE)[1] between 2,000 and 10,000 where the effluent is discharged into a sensitive area, and in all agglomerations with a PE of 10,000 to 15,000 where the effluent is not discharged into such an area.

[1] Population equivalent (PE) in waste-water treatment is the number expressing the ratio of the sum of the pollution load produced during 24 hours by industrial facilities and services to the individual pollution load in household sewage produced by one person in the same time. It is generally assumed that one unit equals to 60 grams of BOD per 24 hours.

Nevertheless, in less developed countries such collection and treatment infrastructure is only available to small portions of their population or parts or urban centres (Fig. 2.2a and b). For example in China, according to the latest available data (2004), only 32.5% of the total population in connected to wastewater treatment facilities (UN Statistics Division, 2011). This means that in the years to come there will be an increased pressure for the development of sewage networks and treatment plants, especially in developing countries.

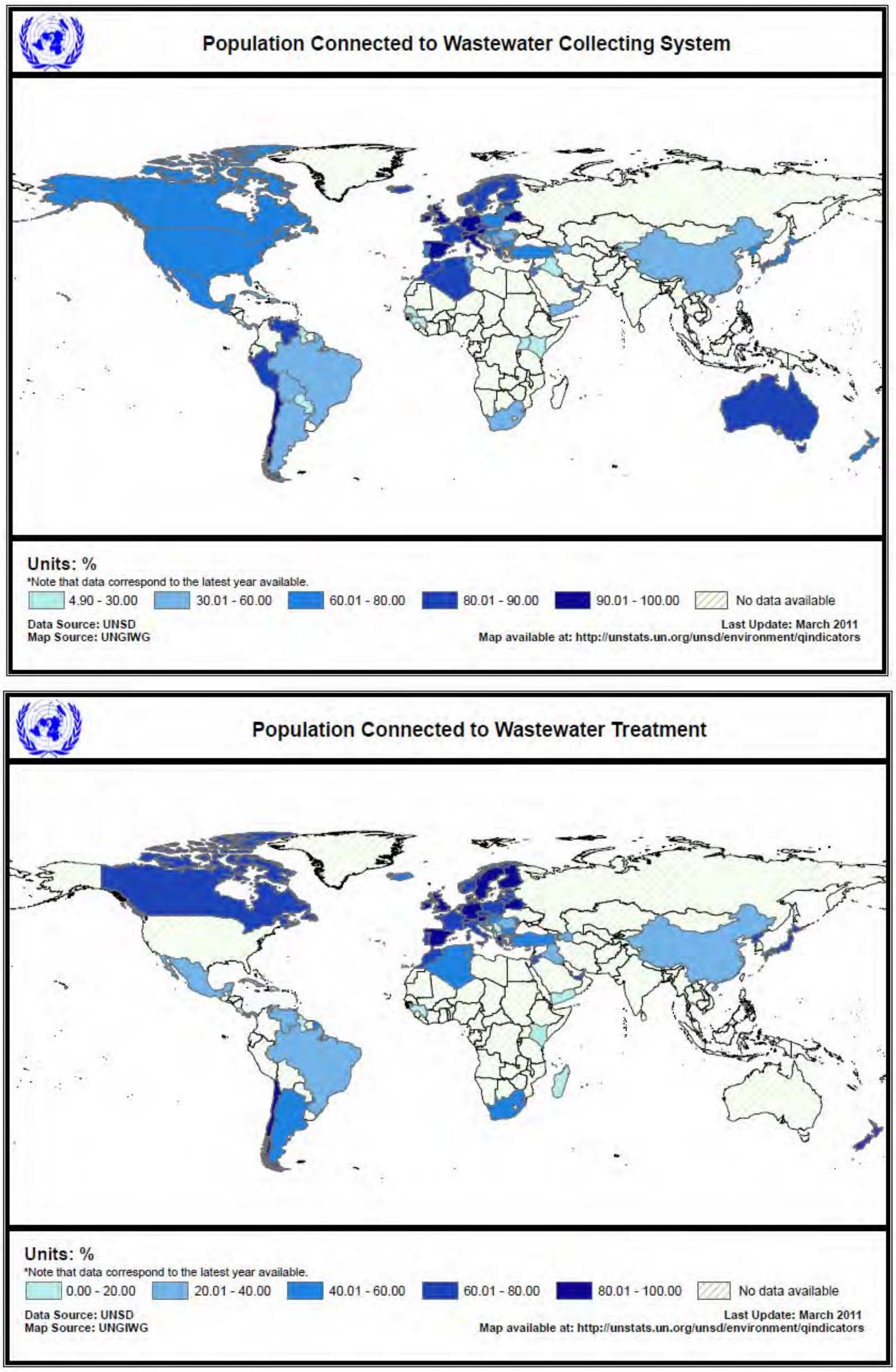


Fig. 2.2. World data on counties' population (a) connected to wastewater collection system and (b) connected to wastewater treatment facilities (UN Statistics Division, 2011).

2. Underground waste collection systems

2.1. Introduction

The use of underground (and semi-underground) systems for the collection of urban waste streams has been more broadly introduced in urban areas within the last 2 decades, even though applications of this kind goes back to the 70's (e.g. Roosevelt inland vacuum system).

The major difference that these systems have, with respect to typical above ground collection, is that the waste containers are positioned underground in pre-fixed places. Thus, they are developed in a form of permanent infrastructure network to facilitate the waste collection activities, instead of being a house specific service employing waste bins, like typical collection schemes. Nevertheless, this development can yield considerable results in both the logistics of waste management and the environmental protection. For example, in older urban areas, conventional door-to-door waste collection is often challenging due to varying topography, climatic conditions, limited space for waste containers and transportation vehicles as well as frequent occupational accidents among waste collector personnel (Poulsen et al., 1995).

The underground systems can either operate as stand-alone collection points or can incorporate automated vacuum collection schemes (AVAC or Automatic Solid Waste Collection system – AWCS, also often referred as stationary pneumatic collection system), in which the waste are pneumatically transported to a centralized facility for further process. Both systems can manage different waste streams (e.g. mixed waste, paper, etc.) with the inclusion of additional collection points or inlet chutes.

2.2. Main types of underground collection systems

The underground waste collection systems can be discerned into two major categories. The first category of underground collection systems is considered to follow a more traditional approach, where waste containers are replaced by underground collection points (Fig. 2.3).

These points are usually employing the underground or semi-underground placement of containers, sited in excavated shafts usually 2-3 m deep, having only their inlets in the surface environment. The most well-known commercial family of such products it the Molok type, taking its name from the Finish Company Molok Oy, which first introduced this concept of deep collection system back in the 1980's.

The waste containers are in the form of a cylindrical shape, as shown in Fig. 2.4, usually placed along public right-of-ways. The capacity of these containers range from 0.6 to 5 m^3. The system is consisted of two parts, the outer shell and the inside bag that the waste are actually placed. Their greater portion is buried underground, whereas on ground level only the inlet structure with the characteristic shape is visible. The collection and transportation of wastes is carried out using specially adapted heavy trucks (Fig. 2.5).

Fig. 2.3. Above ground and underground waste collection systems (source: Ecologia Soluzione Ambiente SpA, 2012).

Fig. 2.4. Types and detail of the Molok deep collection system (source: Molok Oy, 2012).

Fig. 2.5. Waste collection process in Molok type underground waste containers.

Molok type of waste containers are used worldwide for three decades now and their range of applications in terms of waste streams is quite extensive, covering from recyclable paper waste to organic waste and oil. There are also many other companies that utilize this principle (Fig. 2.6) and have introduced their own commercial products (e.g. SULO, OTTO/ESE, USER, SOTKON, Serac, etc.), some of which are fitted with electromechanical systems for elevating the underground waste container to surface.

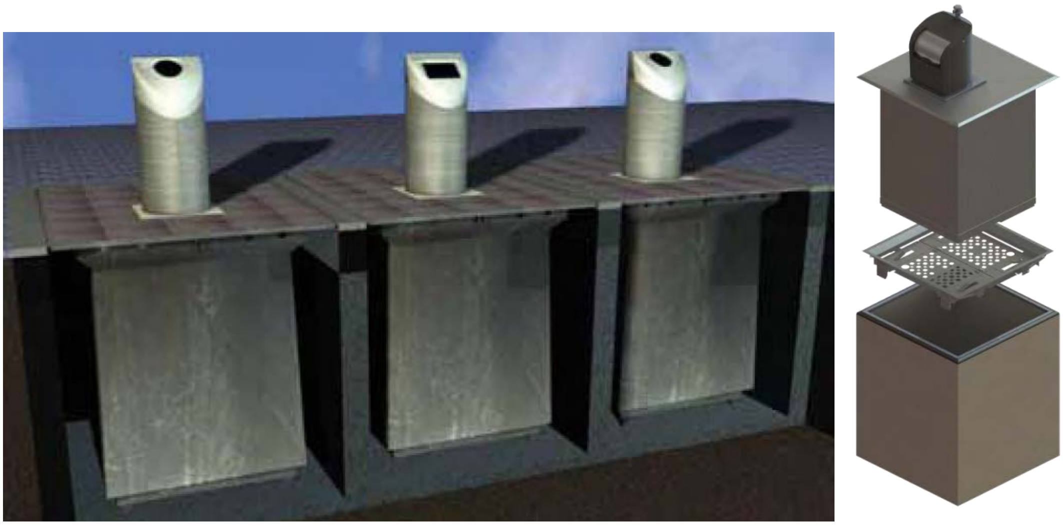


Fig. 2.6. OTTO's Ingenio system for underground waste collection (source: ESE GmbH, 2012).

Furthermore the containers could be fitted with hydraulic compactors and therefore can reduce the volume of the waste. Figure 2.7 is taken by Kogler (2007) and shows what the container – compactor system looks like. On the left hand side one can see the inlets for the underground compactor where waste can be deposited. On the right hand side the underground container is already hydraulically lifted and ready for the emptying process. The collection vehicle loads the full containers and replaces them with empty ones.

Fig. 2.6. Hydraulic underground compactor in normal and emptying position.

The success of the underground containers lies in its superior holding capacity and environmental protection attained, over traditional surface waste containers. More particularly, it offers:

- greater holding capacity than of the same area's surface dumpsters/bins, requiring less frequent collection
- compaction of the waste (through gravity or by mechanical means), increasing their effective capacity by 1.5 to 2.5 times
- improved aesthetics allowing their incorporation in the city's design
- constant temperature conditions, slowing bacterial development and controlling the odor problems, especially in summer time
- limited maintenance requirements and superior protection against vandalism

The use of underground pipeline infrastructure for the transportation of municipal solid wastes instead of vehicles is not a novelty (Zandi et al., 1969). This AVAC technique goes a step further than underground stand-alone systems. The waste is disposed through inlets (Fig. 2.8) to special underground containers and then at selected time intervals, their automated transport is taking place, by vacuum suction through an underground pipe infrastructure (500 mm in diameter), towards a central station. There the waste are sorted and disposed in large containers, to be carried away using conventional methods (trucks) for further treatment, recycling, incineration or landfilling. The method can be defined as a pneumatic sewer system in which solid waste is collected and transported automatically. This means that there is no need for the manual collection from the underground containers using trucks and workforce. Instead, trucks are only used from the central facility onward. However, the system is unsuitable for large items, hazardous waste, waste electric equipment and liquid waste, while there are problems with the handling of cardboard and glass waste fractions.

Fig. 2.8. Typical inlet points for various waste fractions of the AVAC system.

In this method, the piping required is either placed in the shallow underground or follows the path of utility tunnels that already exist or are developed for this purpose. The design life of the piping infrastructure is estimated to be around 60 years. This system offers great flexibility in the placement of the waste containers. These can either be placed in public places or even inside houses or apartment buildings (Fig. 2.9).

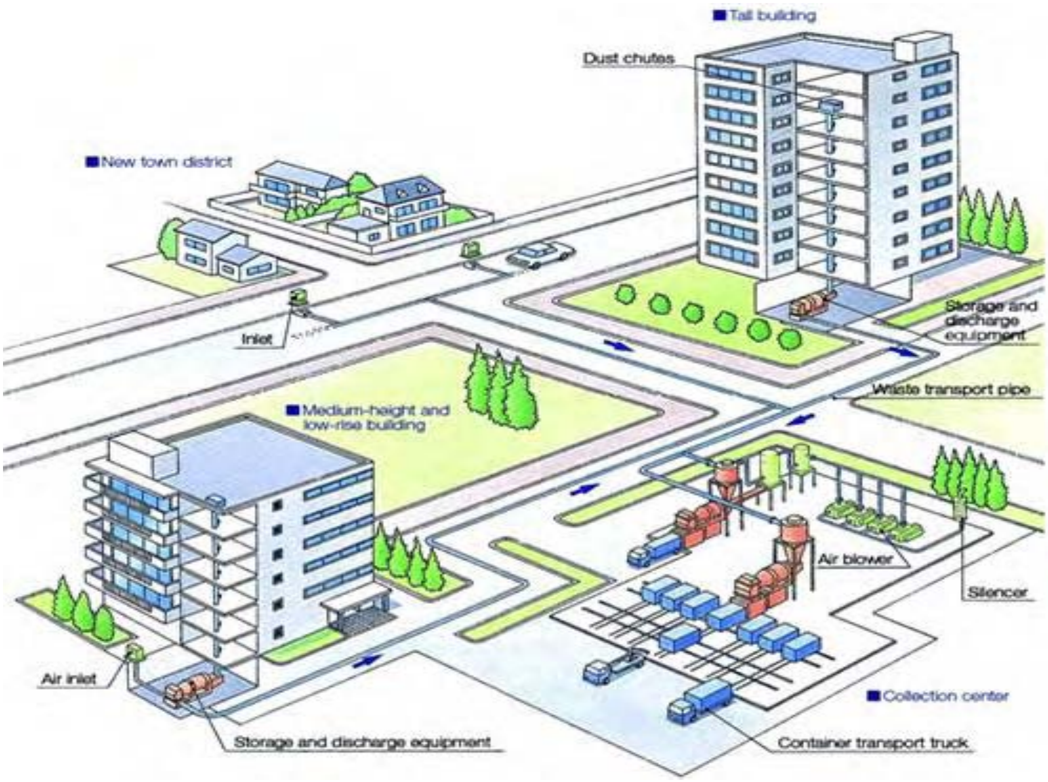


Fig. 2.9. General schematic view of the equipment and the layout used for the AVAC system.

Furthermore, it should be noted that in the absence of pipe infrastructure, mobile vacuum units (fitted in trucks) are available to literally suck the waste from the underground containers and carry them for processing (Fig. 2.10).

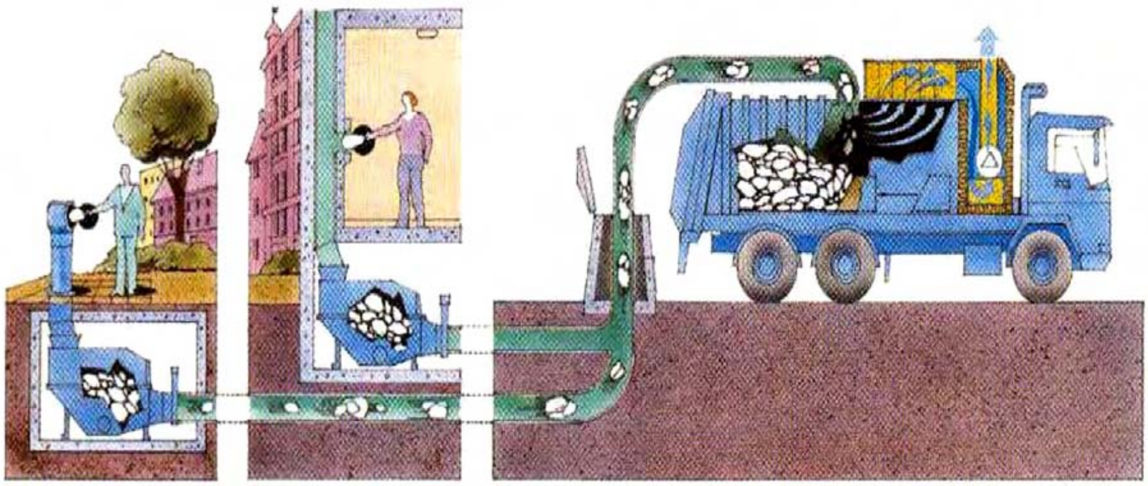


Fig. 2.10. Mobile vacuum units facilitating the handling of wastes from underground waste collection points.

The method has been used originally for the waste handling of buildings and large scale commercial areas (e.g. malls, airports, etc.) but has now been dynamically introduced into urban environments. Especially for the case of historical city centers or places of high touristic attraction where the traditional handling of the waste is difficult due to limitations in accessing the road infrastructure and to the scheduling of operations, the management of waste through underground collection schemes can provide extremely efficient results.

Major benefit from the usage of AVAC system is the minimized operating cost for the waste handling. Of course, greater initial investments are required (Teerioja et al., 2012) but the more economical operation of the system can actually pay off this disadvantage in the long run (Honkio, 2009). Reduced number of waste collection trips are required, a fact that positively influences operating cost, traffic congestion, minimizes CO_2 emissions from the garbage trucks and presents potential space savings (Kogler, 2007). Furthermore, littering and hygienic problems are kept to a minimum as the container overload is decreased and odor issues are better controlled, while at the same time a smooth operation of the system can be achieved 24 hours, 365 days a year, even at difficult situations either as a result of severe weather conditions (e.g. storms) or external events (e.g. strikes, protests, etc.).

In Table 2.2 the major advantages and disadvantages of the underground AVAC system are presented.

Table 2.2. Advantages and disadvantages of the AVAC system.

Advantages	Disadvantages
Minimized operation cost and long term savings	Heavy construction operations needed requiring high investment costs
Ability to collect apparently all waste streams	Cannot collect large items, bulky wastes, WEEE and has difficulties with glass wastes
Flexible system with the ability to easily adopts to changes	After installation the flexibility of the system is reduced
Minimized usage of garbage collection trucks in urban areas	Truck transportation is not eliminated
Minimized noise, aesthetic pollution and odor problems	Risk of problems related to pipe blockages
Release of surface space for community needs or development	Public willingness and training to proper disposal required
Enhanced safety for collection workers (hygiene, accidents, etc.)	Experienced workforce is required

The above indicate that the use of underground systems result to a more efficient management of urban waste, enhancing both the city's environmental conditions and the financial aspects of the operations.

2.3. Cost issues

Some data regarding the reduced collection cost are presented hereinafter. The first is from a relevant study in Netherlands undertaken by NVRD (Koninklijke Vereniging voor Afval en Reinigingsmanagement - Dutch municipalities association for waste management and cleaning). According to this study (NVRD, 2003) the collection cost by using underground containers is more cost-effective solution than the relative of traditional schemes (Table 2.3).

Table 2.3. Yearly average collection cost for residual waste in Netherlands by household (NVRD, 2003).

Collection System	Major cities (e.g. Amsterdam)	Large cities /towns	Small towns and rural areas
Bags	71	71	88
2-wheel containers, rearloading trucks	89	67	66
2-wheel containers, sideloading trucks	46	32	58
2-wheel containers with 2 compartments	68		42
2x2 wheel container		75	71
Communal containers	70	87	54
Underground containers	67	50	38

The data from the second study come from the economical comparison between a conventional collection system and a stationary vacuum system as carried out by SWECO (2005) in Sweden and presented by Törnblom (2008). The purpose of the study was to identify best waste management practices for the development of a new housing project in Västra Sjöstaden, comprising of 2095 apartments.

The study includes investment cost (construction, technical equipment, replacement and maintenance, etc.), operating cost (collection, energy, etc.) for these two systems, over a 20 year period. Furthermore, cost related to the release of surface space is also included, taking into account average annual rents for commercial premises (1,500 SEK/m^2 per year). The major findings of the analysis are presented in Tables 2.4. In Table 2.5 the costs per apartment are given, with 6% cost of capital, a 30 year's depreciation period, with no rental income, excluding VAT.

As it is obvious the investment cost for the automated vacuum waste collection system is considerably higher, almost twice as much of the traditional system. Nevertheless, its greater efficiency in operation can yield very promising results, even without the inclusion of the rental of the released surface space, thus making it a more profitable investment strategy, over typical surface waste collection.

Table 2.4. Investment and operating cost comparison of two waste collection systems for the Västra Sjöstaden project (Sweco Viak AB, 2005 - Törnblom, 2008).

CALCULATION (with 4% rental income ground floor premises)	Investment cost for the collection system (SEK)	Operating cost (SEK/year)	Rental income from released surface space (SEK/year)	TOTAL Operating and capital cost (SEK/year)
Manual handling, containers (one reinvestment for containers at 10th year)	27,133,043	2,814,839	-	5,083,189
Underground waste transport system, primary and secondary network	44,275,000	823,099	-2,049,942	2,030,990

Table 2.5. Cost per apartment of the two waste collection systems for the Västra Sjöstaden project (Sweco Viak AB, 2005 - Kogler, 2007).

Preliminary calculation per apartment	Investment cost (EUR per apartment)	Operating costs (EUR per apartment per year)	Total costs - 6% cost of capital (EUR per apartment per year)
Manual waste handling	1,406	130	232
Stationary vacuum system	2,254	43	206

Note: The SEK to EUR exchange was made by Kogler (2007) (1 EUR = 9.37589 SEK).

Another detailed project cost analysis (capital and operational expenses) of the AVAC systems commissioned by ENVAC with respect to the alternative use of EUROBIN waste containers, for 10,000 flats, is presented in Table 2.6 (WIN, 2011). It is shown that there are considerable benefits especially in the operational expenses, with the cost per flat being almost three times lower for the ENVAC's system (GBP£ 20.9) compared to the EUROBIN approach (GBP£ 67.1) while the two systems present roughly equal results in the capital expenditure required for their development.

Table 2.6. A comparison of Envac vs. traditional collection methods using Eurobins for a development of 10, 000 flats. Comparison over 30 years (source: WIN, 2011 with data provided by Envac).

Capital Expenditure (CAPEX)	**ENVAC**	**EUROBIN**	**COMMENTS**
Eurobin cost	£0	£2,550,000	Total 1700 bins x £250/bin, replaced every 5 years
Envac capital cost	£11,000,000	£0	Design, supply and fix all pipe, inlet, collection station
Bin room housing cost	£500,000	£10,625,000	Eurobin, 1700 bins @ 2.5sq.m. per bin @ £2500/sq.m. Envac is for building to house collection station
Trenching cost	£1,100,000	£0	
Total Capex	£12,600,000	£13,175,000	
Capex per flat	£1,260	£1,317.50	
Capex per flat/year	£42	£43.92	
Operational Expenditure (OPEX) per year			
Envac full service	£98,000	£0	Service/maintain Envac system
Envac energy cost	£11,000	£0	Power to run fans, compactors etc.
Eurobins maintenance	£0	£17,000	4% per year to replace lids/castors/vehicle damage
Eurobin annual clean	£0	£13,600	£8 per bin per year
Eurobin portering costs	£0	£160,000	1700 bins will require 8 full time staff @ £20k p.a. to move bins to kerbside and back to bin store
Waste collection cost*	£100,000	£480,000	£10/flat/year with Envac - £48/flat/year without Envac
Total Opex/year	£209,000	£670,600	
Opex per flat/year	£20.90	£67.06	

Finally, one more other older study is presented conducted by BoDAB (1999), a company specializing in operations and maintenance for housing in Sweden, in 1999. The study compares the existing automated waste installation in the Södra Station (Southern Station) area in Stockholm with a hypothetical system for manual waste collection in the same area according to regulations and rates in 1999 (Table 2.7). It covers the waste generated from 3,240 dwellings and three office buildings by a pneumatic system (AVAC) having 178 gravity chutes. It can be seen that the total annual costs per apartment per year is around 25% lower for the case of the AVAC system. Nevertheless this mainly due to the urban redevelopment offered in the city where the free space that emerges from the removal of the bins is rented.

Table 2.7. Comparison of costs per dwelling in Södra Station, Stockholm (BoDAB, 1999 Kogler, 2007).

Preliminary calculation per appartment	Investment cost (EUR per apartment)	Operating costs, collection system per apartment, (EUR/year)	Capital investment (EUR/year)	Rent loss due to garbage and valve rooms (EUR/year)	Total annual costs (EUR/year)
Manual waste handling	1,259	64	39	104	207
Stationary vacuum system	1,479	52	82	18	152

The above studies indicate that a strong financial potential exist in the case for pneumatic waste management, especially in the systems operating cost. However the capital expenditure required needs to be addressed more in a more explicit manner and therefore the proper sizing of the AVAC system can be a parameter of great importance to it. It seems that the system can be more promising, in terms of financial appraisal, in areas where economies of scale can be achieved; that is if more inhabitants and their waste can be managed per inlet chute and per central service station. Furthermore, it is suggested that more accurate cost assessment of the total cost of the service throughout the project's life must be made available, so as to be able to draw more definite conclusions regarding the feasibility of the AVAC system.

3. Underground hazardous waste repositories (UHWR)

The disposal of hazardous waste in an environmental friendly, sustainable and cost effective manner is the one of the main challenges of today. The utilization of underground space for the development of hazardous waste repositories has shown a great number of advantages over conventional surface facilities (ITA, 1994). These derive mainly from the fundamental characteristics of underground space; namely the opacity and the natural protection offered which allows for enhanced protection from both internal and external processes and possible threats, ensuring minimal impacts to the biosphere. There is extensive experience of these type of underground facilities especially in Europe, where several repositories are currently in operation, utilizing at the moment old mine sites that are converted to hold hazardous waste (Benardos et al., 2006).

Even though hazardous waste streams derive mainly from industrial activities and in the majority of cases in areas far from the center of the cities, there are still problems with the management of such waste in urban areas. One of the most common examples of these types of problem can surface when undertaking major urban redevelopment activities in areas where industrial installations used to exist in the past. These “brownfield” cases can reveal extensive pollution levels of hazardous waste and toxic elements. Thus, remediation activities become number one priority and a major task to be completed. In these cases the “on-site” disposal strategy, especially when taking place underground, can be of great assistance. “On site”, has the meaning of disposing the hazardous waste generated or found within the boundaries of the producer’s site or in the vicinity of the affected area.

The main parameters that are now making available the adoption of such strategy is the current state of technology in the field of underground construction, along with the development of efficient engineering/technical barriers, which can provide adequate and feasible solutions in order to overcome problems or site limitations related to unfavorable geotechnical or hydrogeological conditions. The “on site” disposal offers (Kaliampakos et al., 2009):

- Minimized transportation cost and related risks.
- No export of the environmental problems to other areas.
- Tailor made solutions to meet the waste’s special requirements.
- No requirements for the interim storage of the waste.
- Independence from other off-site disposal facilities.

Possible negative issues that might arise and should be further investigated are the limitations on the availability of required area to develop the facility and problematic geological and hydrogeological conditions (geological barriers) in terms of containment. The latter is the most important issue to be addressed and a possible strategy to do so is to develop a system of robust and efficient technical barriers which could guarantee the waste’s long term containment.

When the “on-site” underground disposal is adopted, the benefits from such a solution combine the advantages gained from the underground siting of the repository coupled with the specific opportunities which are derived by the proximity between the waste affected areas and final disposal sites. Thus, new facts are brought about, which allow the tackling of existing obstacles regarding the whole management and disposal of hazardous waste in an economical and safe manner.

Leaving alone the pros and cons of this solution, it should be noted that each case should and must be evaluated on a unique project basis so as differentiations and adjustments should be made to meet the specific needs and individual waste and site characteristics.

4. Underground sewage (waste water) treatment plants

The use of man-made underground installations for the development of sewage treatment plants (STP) is constantly gaining ground over traditional above-ground installations. In these facilities a typical processing of the waste water is made in underground environments that are usually excavated in rock formations, creating a series of caverns and tunnels or are developed in underground concrete structures using the cut-and-cover technique (excavation from top, development, covering). The first construction type is used in cases of favorable topography and rock properties, while the latter is usually employed in cases where low strength rocks exist in the area and the construction takes place usually in shallow depths.

The experience from several projects reveals that the main driving forces behind that are the release / reclamation of surface land, as well as the environmental protection attained by such facilities. Underground facilities of this type are in operation for more than 60 years now. Nonetheless, in the last two decades the pace of adopting such solutions has been increased. Scandinavian countries have a significant tradition in this field, while now there has been a remarkable progress in the development of underground waste water treatment plants taking place in Asian countries (Fig. 2.11).

Fig. 2.11. Inside views of the rock caverns and the process installations in the Stanley underground STP (Hong Kong).

The utilization of land for other purposes, especially in areas with limited surface availability or in cases where high land value is experienced (i.e. densely populated urban areas) offers direct and indirect economic benefits. The direct benefits derive from lower capital costs associated with land acquiring as only limited surface infrastructure is required, minimized length and cost of sewage transport tunnels as the treatment facility can be located within city boundaries, being as near as possible to the source of production rather than in remote areas. The indirect benefits are related to the economic and/or social value generated from the utilization of the released / reclaimed land. Furthermore, indirect benefits are related to the value of the neighboring properties that could be positively affected by the removal of the surface facility as a result of its underground relocation or by the underground development of the plant from the beginning inflicting no impacts to surface environment.

The environmental protection and the minimal impacts to the natural and human environment, compared to a respective surface facility, is attained, as the whole sewage treatment process is taking place underground. This means that there are no visual impacts, while, at the same time, enhanced control of odor problems and noise pollution are achieved. Moreover, the underground development could assist in tackling NIMBY ("Not In My Back Yard) arguments. Thus, in places of great natural beauty or in densely populated areas, by placing the treatment process underground strict environmental standards are met and the support of the local communities is attained.

The underground placement of the facility also limits the effect of external factors on the chemical/microbial processing taking place there. The relatively constant temperature conditions achieved, the absence of ultra-violet light as well as the avoidance of rainstorm events allow for a better control and consequently more efficient de-pollution process of the waste, minimizing at the same time odor emissions.

To gather all advantages of underground STP the following have been stated (Benardos et al. 2010):

- Superior environmental protection with completely controlled odor, visual and noise impacts.
- High availability in the siting of the facility and high potential/flexibility in future upgrade/expansion of the plant.
- Potential capital savings as of limited spending for land property acquiring and of minimized transport distance (and respective infrastructures) of the sewage.
- External benefits from land release/utilization and social benefits to the neighboring communities
- Improved quality of processing allowing for enhanced de-pollution capabilities.

The disadvantages of underground STP's are mainly related with the higher construction cost as well as operational expenses related to the constant use of ventilation and lighting. Nevertheless, the importance of underground sewage treatment plants in setting a new type of development, aiming at improving living conditions, is something that cannot be denied, despite any drawbacks. The inclusion of external costs in a cost-benefit analysis usually reverses the situation and shows that the development of underground sewage treatment plants can be the most cost-effective choice.

III. Analysis of Selected Case Studies

1. Underground waste collection systems

The number of cities that utilize underground waste collection systems, either stand alone underground containers or automated vacuum collection ones is substantial. Thus, in the examples presented hereinafter only some notable cases are given. These case studies present one of the world's oldest operating AVAC system, some new housing projects in Europe and Middle East that employ similar techniques, cases from heritage city centers, cases where the change of the traditional door-to-door system to underground collection was implemented, as well as some special purpose applications (e.g. recreational, religious areas) that the underground management of waste has been adopted.

1.1. Roosevelt Island (NY, USA)

The Roosevelt Island automated vacuum assisted collections system (AVAC) was commissioned in 1975 and since then it handles 10 tons of waste on a daily basis from the island's 16 apartment complexes (Fig. 3.1). It eliminates the necessity of noisy and potential dangerous collection trucks on the Island's narrow and densely populated streets. Unsightly and odorous piles of bags and dirty dumpsters are non-existent facilitating to a cleaner, healthier and quieter environment for the people of Roosevelt Island.

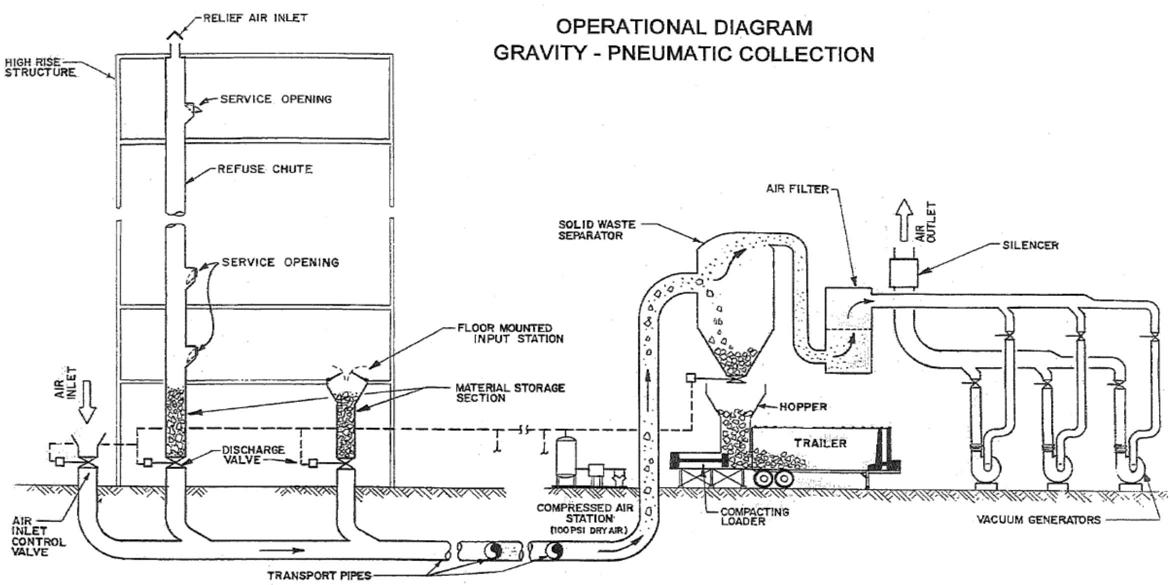


Fig. 3.1. Schematic diagram of the Roosevelt island AVAC operation.

A network of 20-inch tubes takes garbage from the island's residential towers, collecting them from every floor, to a central collection point (RKA, 2012). At this facility the waste are separated and packaged to containers for their subsequent transport and process. The system is activated every several hours (5 times every day) when a computer triggers six centrifugal turbines in the basement of the AVAC building, creating the vacuum that pulls the accumulated waste materials. The system is divided into two separate subsystems (East and West sides), each capable of handling in excess of 20,000 pounds (~ 10 tons) per hour.

It should be noted that the system, in its 4th decade remains effective and efficient. Roosevelt Island was the only New York City Sanitation District to have uninterrupted collections, during the severe weather conditions in winter 2010 (snowstorm), when garbage trucks in the rest area of New York were used to plow snow and it took almost 3 weeks to restore the city's waste collection activities to normal level.

1.2. Disney World (FL, USA)

The underground automated vacuum collection waste (AVAC) system in Disney World, Florida, was put into operation in the early 1970's and was the first underground waste collection scheme ever employed in the United States. The systems operate on a 24 hour basis and transport the waste from all points around the park to a central location where they are processed and recycled. The pipe infrastructure is located inside the utility tunnel network (utilidors) that is developed below ground level (Fig. 3.2). The main network consists of around 2 km of pipes and facilitates a total area of 1,200,000 m^2. Recently, an upgrade to the system has been made and new pipe installations have been added, with the construction following the microtunneling method (Fig. 3.3) (Robinson Construction, 2012).

Fig. 3.2. "Utilidors" in the Disney world facilitating amongst others the pipe infrastructure for the AVAC system.

Fig. 3.3. Microtunelling operation for the construction of underground pipe AVAC infrastructure.

1.3. Wembley city (Great Britain)

The Wembley city is a major urban development project covering 85 acres of land, surrounding the Wembley stadium. It comprises of 4,200 flats, as well as retail shopping, hotel and leisure facilities. The automated waste collection system is operating there from 2008 handles 160 tons of waste per week (Fig. 3.4). It has a total of 252 inlet points used for the collection of four fractions of waste (rest, organic food waste, mixed recyclables with paper, card/cardboard). The inlet points are installed in each apartment building, near the exit area, in which residents dispose the waste (Fig. 3.5).

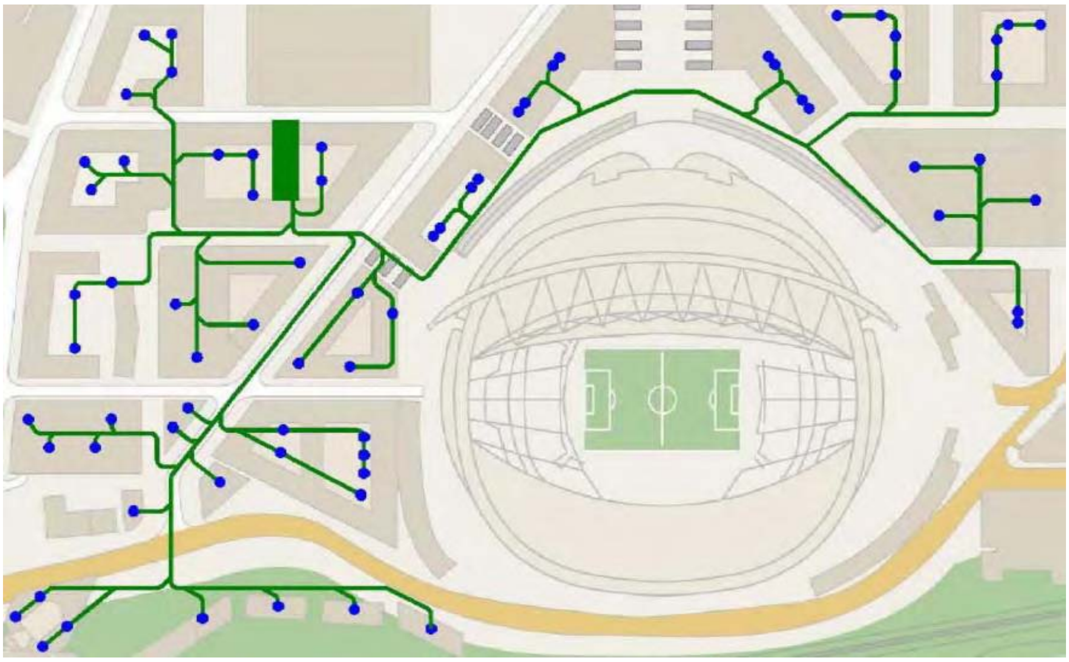


Fig. 3.4. Schematic drawing of inlet points and the underground pipe network for the AVAC development in Wembley city.

The system vacuums the waste several times a day, or when the installed sensors identify that the temporal storage container is full, to a collection centre through 2.5 km of underground installed pipes. At the collection center the waste are separated, compressed and packaged to containers. The transport air used after its purification processing is released into the atmosphere (Envacgroup, 2012a).

Until now the system shows remarkable efficiency. Blockage problems due to oversize bags are rare and no manual unblocking has taken place, as the system has the ability to increase vacuum pressure and control such issues. The result of the project in terms of environmental protection is quite substantially. First of all, it is estimated that about 400 tons of CO_2 emissions per year can be saved using this system over a conventional waste collection approach, as reduced waste collection vehicle movements by 75% are achieved (WIN, 2011). Furthermore, the recycling rates amongst residents shows a considerable improvement (40-45% of all waste is recycled) compared with the figures of the overall Brent Council's area (21% in 2006/07), part of which is the Wembley city.

Fig. 3.5. View of the Wembley city's apartments and AVAC collection points.

Lastly, the AVAC system allowed for the saving of 1865 m^2 for residential properties (equivalent of 22 flats), provided additional 62 car parking spaces and a further 1106m^2 for other commercial uses.

The total investment cost for the development of the system was around 7 million GBP while the construction activities lasted for approximately 2 years. The operating cost of the system is also paying off for the residents. Brent Council which is responsible for the waste collection charges a yearly rate of 60 GBP per household in the Wembley city, while for all the rest Brent area, the collection cost is around 90 GBP per annum (WIN, 2011).

1.4. Yas Island (UAE)

Yas Island is a major real estate property development in Abu Dhabi, incorporating sports, leisure and commercial facilities. It features an automated vacuum waste management system, consisting of 43 inlet points, installed around walkways or in buildings (Fig. 3.6) and a total of 5.3 km of pipes with a handling waste capacity of about 40 tons per day. At each inlet point there is one chute for organic matter and one for waste that can be recycled, such as paper, tins, glass and plastic. Once disposed of at the inlets, the waste will be drawn by vacuum to the central processing plant after covering a maximum travel distance of 2.9 km. The vacuum system works on demand and it is only activated when required, being able to empty either identified collection points or all of them at once (Recycling portal, 2010).

Fig. 3.6. Inlet points for the AVAC system in the Yas Island.

With the use of this system efficient waste handling, as well as minimum disturbance from waste collection operations are achieved in the area. The capital expenditure needed to install the system was four times higher than of a conventional system, however, the operating costs is only about 20% of those required in a traditional system.

1.5. Adu Dhabi (UAE)

In Abu Dhabi a major project for the replacement of the traditional surface waste containers / bins is under way in an attempt to tackle waste collection cost, odor and littering around surface collection points (containers) and, thus, improving the aesthetics and ensuring a cleaner environment for residents (CWM, 2012).

This project includes the installation of underground waste containers at about 400 locations throughout the city. Each one of these collection points has a total capacity of 20 m^3, using multiple steel containers, positioned in pre-excavated shafts. It uses an electro-hydraulic system for opening the lid of the system (Fig. 3.7).

The containers are fitted with censors sending alerts when 75% full, enabling more efficient waste collection by reducing unnecessary traffic. It is estimated that the large storage capacity as well as the compaction of waste will reduce the number of collection trips from three a day to one or two every two days, hence reducing transportation cost. Specially adapted waste trucks will lift the containers out of the ground, empty and reposition them.

The new underground system will provide centralized and strictly regulated refuse collection facilities for approved users, while barring access to non-approved users and preventing unauthorized dumping of waste.

Fig. 3.7. Underground waste collection system operated in Adu Dhabi.

1.6. Barcelona (Spain)

In the city of Barcelona the first automated underground vacuum collection system was developed in the Olympic city (Villa Olympica) in 1992, as part of the city's renovation for the 1992 Olympic Games. Initially, 241 inlets were installed in the area, which handled a single waste fraction from the 2,900 dwellings (Envac Concept, 2003). The first extension to the system (2002), increased the number of inlets from 241 to 480, while also the capacity of the system was increased and enabled for the collection of two waste types through separate inlets, facilitating a total 4,600 houses. The third extension took place in 2009 with the expansion of the central station, doubling its equipment in order to be able to transport the waste from 16,000 houses (Envac Concept, 2010).

Barcelona is in the forefront of automated waste collection system utilization having a consistent planning policy for the issue aiming at a complete integration of such systems in the city. Now apart from the Villa Olympica installed system, has six more automated waste disposal systems in operation (22@, 2004 Forum – Fig. 3.8, Diagonal Poplenou, Santa Caterina, etc.), serving up to half a million residents.

These systems handle not only the household waste but also include waste from shops, offices, restaurants, hotels and from a variety of other private and public companies which are also connected to the system. Especially for commercial users a new type of waste inlet has been developed. The larger inlet door for commercial users is designed to take 110-litre plastic bags and requires an electronic key to open it. This provides a way of generating user statistics in terms of waste production and it could allow for the charging of different users at different rates.

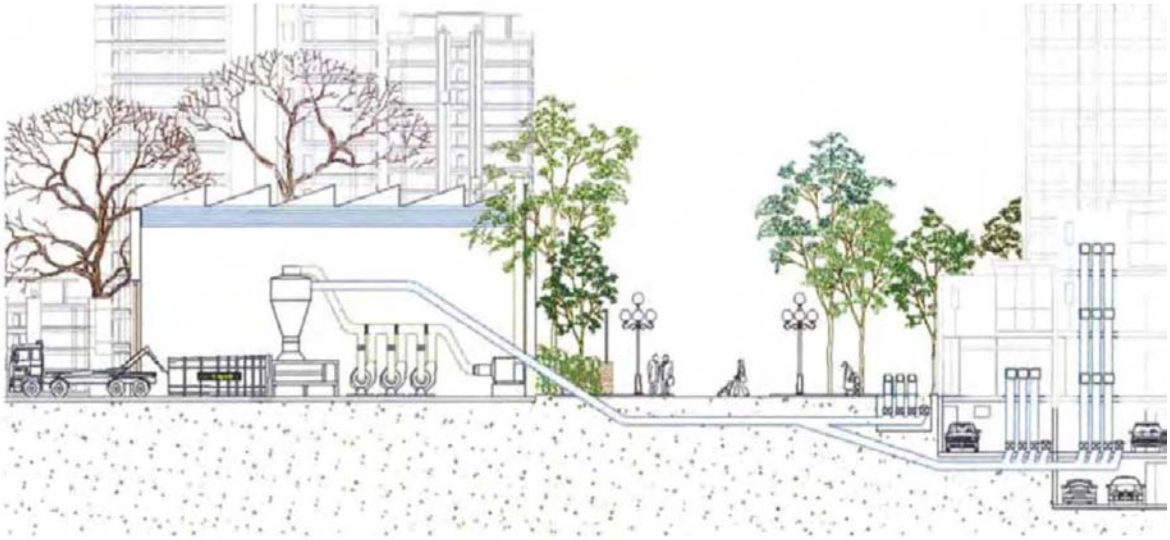


Fig. 3.8. Schematic view of the automated waste collection system operated at 2004 Forum area.

1.7. Leon (Spain)

Leon is a medium-sized city and its main characteristic is its important historic center, with a very rich cultural and built-up heritage. The problem lies in the city's severe shortage in infrastructure that made typical collection activities difficult, deteriorating both traffic conditions and the heritage roads and buildings. The introduction of automated vacuum waste collection aimed at a smooth collection operation without having all the aforementioned drawbacks.

The system handles two waste types organic waste and paper / cardboard. Glass waste cannot be collected by the system and for its collection the traditional containers are used. The area covered by the AVAC system has 4,000 inhabitants as well as 150 bars and restaurants that produce a total of almost 10,000 kg/day of waste and 1,000 kg/day of glass (COST-C8, 2010).

The collection points are differentiated according to their users, into residential (for families residing in the area) and commercial (mainly bars and restaurants) drop off points. In total, there are 71 collection points and the maximum transport distance covered by waste until reaching the central collection terminal is roughly 1.3 km. At the central station a suctioning plant including extraction tubes, waste separation centrifuge, waste compactor, internal container transport system and air purification equipment are installed.

The total cost of the project commissioned in 2002 amounted to 5.2 million Euros while, annual maintenance costs are estimated to be at around 100,000 Euros.

1.8. Romainville (France)

In France, Romainville is the first municipality to install an underground automated vacuum waste collection system. The project is part of an approach outlined by the ANRU (national urban redevelopment agency) and launched in 2008 by the town of Romainville and its partners, neighboring towns Les Lilas and Bagnolet. The AVAC system in Romainville (2,800 dwellings - 9,000 inhabitants) was commissioned in October 2011, and a further 1,600 dwellings in the Les Lilas area is to be connected in the near future.

The system consists of 179 inlet points (Fig. 3.9) and of 4.1 km of transport pipes placed 2 m below ground level. The inlets that have been made available for the 2,800 dwellings are emptied automatically two to three times a day and its takes approximately 45 minutes for all the inlets to be emptied. The capacity of the system is about 12 tons per day (Girus ingenierie, 2012).

Fig. 3.9. View of the inlet points positioned outside the apartment buildings in Romainville.

The contents of the inlets (residual household waste and selective waste) are transported by the vacuum generated by two turbo-compressors to the central facility. The waste is then compacted in containers and sent to the residual household waste incineration plant or the sorting centre. During the first phase of the project, an extensive information and training campaign was launched in order to acquaint residents with the proper usage of the system.

Operational costs are estimated at €120 to 130/tn of waste and tenants' charges are reduced by approximately €100-120/dwelling/year. The total investment of the project was approximately €13 million.

1.9. Hammarby Sjöstad (Sweden)

Hammarby Sjöstad is a part of Stockholm municipality, currently undergoing major urban redevelopment. Especially for this area the city of Stockhold has proposed an environmental programme with the aim of halving the total environmental impact in comparison with a district built in the early 1990s. The principal environmental objectives for waste management were to reduce the total amount of household waste, reduce waste collection by heavy traffic and introduce source separation. The use of automated waste collection system has been introduced (Fig. 3.10) with the aim to reduce the total amount of household waste, reduce traffic generated by waste collection trucks and introduce source separation.

Fig. 3.10. Collection points of the AVAC system fully integrated in the urban environment of Hammarby Sjöstad (source: Envacgroup).

At the completion of the infrastructure and housing project, estimated at 2016, Hammarby Sjöstad will comprise more than 11,000 apartments on the southern shore of Lake

Hammarby (most of them constructed in the 2000s) and more than 2,000 apartments on the northern shore (constructed in the 1990s) totaling a number of 35,000 people that live or operate in the area.

At present the system's capacity is about 12 tn/day, utilizing 457 inlets and almost 12.5 km of underground pipes, collecting three waste types (residual, organic food waste and paper). At its full development the system's capacity will be increased to 15 tons/day gathered from a total of 650 inlets and 16 km of pipes (Envacgroup, 2012b). One of the results of the vacuum system is that the traffic with heavy waste collection vehicles has been reduced by 60%. On the same time, residents benefit from reduced waste collection fees.

For the neighborhoods of Sickla Udde and Sickla Kaj mobile units are in operation since limited residential development is planned. The system there facilitates the collection of two waste fractions (mixed, food waste), with the collection taking place on a weekly basis.

1.10. Porimao – Algarve (Portugal)

In Portimao area, a popular recreational area in Portugal, the retrofitting of the aboveground waste containers has taken place and the development of underground collection points was introduced to the town's waste management system in 2010. Amongst the main reasons that led to for this change was the problems related to the aesthetics as well as hygiene impacts near the surface waste containers especially in summer months related to the odors generated, the presence of rodents, flies, etc. Further issues were the improvement of both recycling ratios and the flexibility in collection frequency.

More particularly, conventional wheeled bins and containers (240 lt to 1,100 lt) have been replaced by 240 underground collection points that have been developed over the city in precast concrete silos. Each silo features a hydraulically-damped hinged metal lid, which is only raised when the container needs to be emptied. At all other times, only the waste inlet is visible above the surface (Fig. 3.11a). Each of these points (cluster) can collect waste from 4 streams in respective containers with a capacity of 3 m^3; 3 of them are used for recyclables (paper/cardboard, glass, plastics) and one for residual waste. Furthermore, at specific areas the combination of containers can vary accordingly to meet the needs of specific waste streams.

What is also important is that the existing fleet of refuse trucks (conventional rear loading collection vehicles) is used for the collection activities (Fig. 3.11b), after the installation of a top-mounted loader crane equipment.

According to EMARP (Empresa Municipal de Água e Resíduos de Portimão) the municipal organization responsible for the waste management, the savings offered by the adoption of the system reach up to 18% as compared to the old collection scheme (Bates, 2010). The truck collection crews have been reduced down from 3 to 2 persons while an increase of productivity of 10 hours per week per truck-crew is attained. The current capacity of the system is around 32,000 tn per annum and the expansion of the system to cover the whole city is planned.

Fig. 3.11. (a) Underground waste containers in Portimao (b) Waste collection process of the containers using specially adapted trucks.

1.11. Mecca - Masjid al-Haram (Saudi Arabia)

In Masjid al-Haram (Holy Mosque) is the world's largest mosque (Fig. 3.12). It is located in the city of Mecca and surrounds the Kaaba, the most sacred site in Islam. It covers an area of 356,800 square meters (88.2 acres) and each year about 13 million pilgrims visit the site (1 million in peak days).

Fig. 3.12. View of pilgrims in the Holy Mosque.

Collection and transport of the solid waste generated during the peak times present a challenge to the authorities. The congested streets and high population density in the mosque and its surrounding plazas make the traditional methods of collecting and transporting solid waste impractical. Thus, tons of waste accumulates awaiting the arrival of the collection trucks, creating severe problems and health hazards and plans for the development of a vacuum system have been investigated in the past (Al-Ghamdi et al., 2003).

The underground automated vacuum system that is currently under development upon finishing will be the greater facility of its kind in the world, with a capacity of 600 tn per day, or 4,500 m^3 of waste (MariMatic, 2011). Several underground collection points (300 to 600 lt capacitiy) with their respective inlet chutes will be installed, and from there, the waste will be transferred through a pipe network 20 kilometers to the waste collection terminal for compaction and further transfer to the landfill. The waste will be transported with speeds up to 100 kmh (30% more than of respective systems), while the longest collection distance is estimated to be about 4 km.

A major feature of the system is its low energy consumption (1/3 of respective AVAC systems) as it utilizes smaller diameter pipes (200-300 mm) and a circular ring-line piping system for the core pipe network.

It is expected that the automated system will more efficiently perform the job now being done by 2,000 laborers and around 40 cleaning equipment units. On a second phase of the project the system is expected to be extended, so as to cover the whole mosque area. The development of the project is expected to cost around 50 million Euros, while this figure is expected to further increase with the expansion project. The project is expected to be fully operational by spring 2013.

2. Underground hazardous waste repositories

2.1. The underground hazardous waste repository at Lavrion Technological and Cultural Park (LTCP)

The Lavrion Technological and Cultural Park (LTCP) is located in the same area where the ancient Greeks started the underground exploitation of silver in 7th century BC. These deposits along with the ancient mining residues (off-grade ores) were further exploited for lead extraction from the 19th century until the early 90s. The complex bears a significant mining history and constitutes a unique monument of industrial archaeology. The effort for its restoration began in the past decade. It was decided to establish a science and cultural park in the area. Nevertheless, even if the building's restoration had progressed rapidly, land remediation only focused on the most critical areas so as to mitigate immediate risks. Most of the ground was covered with waste and slug materials, while the grade of the contamination varies, because of the successive transfer and deposition of the wastes that took place during the lifespan of the metallurgical plant.

The chemical analysis of soil samples in the LTCP area is presented in Table 3.1, revealing high percentage of lead, arsenic, zinc, cadmium and copper (Karachaliou et al., 2005). The test results indicated that the vertical and the horizontal distributions of the pollutants vary significantly and that almost the entire area has to be treated, to an average depth of 4 meters.

The LTCP remediation project aimed at the complete environmental restoration of this brownfield site. The project included the disposal of approximately 115,000 tons of contaminated soil in a special "dry tomb" landfill structure and the development of an underground repository to hold the most hazardous wastes found in the Park (Kaliampakos et al., 2007).

Table 3.1. Concentration of hazardous contaminants in the LTCP area.

Contaminant	Average concentration (ppm)	Max concentration (ppm)	Canadian standards - industrial use (ppm)	German standards - industrial use (ppm)
Pb	23,534	75,500	600	2,000
Zn	35,638	97,922	360	-
As	4,976	60,725	12	140
Cd	94	1,509	22	60
Ni	179	1,100	50	900
Cr	4	30	87	1,000
Cu	2,966	22,000	91	-

The underground repository was especially designed to store approximately 5000 tn of hazardous waste (with monitoring and retrievability option), having high concentrations of heavy metals and toxic metalloids, such as arsenic, lead, cadmium and zinc. These waste are primarily derived from the restoration of the "Konofagos" building, which used to serve as a fume air-filter facility. The building is considered to be severelly polluted since it is covered by dust having an arsenic content of 4% - 8% (Kaliampakos et al., 2009). It has been decided to proceed with such an "on-site" underground storage arrangement, so as to attain:

- the complete containment of the hazardous waste
- a cost-effective storage scheme, which could act as a model example in other similar cases worldwide.

As no centralized underground or above ground hazardous waste disposal repository exists in Greece, the only other available option was to export the waste. However, this alternative would require a complicated transport procedure and a very high disposal cost. With the development of the LTCP repository the storage is made possible in a cost-effective manner with respect to the required export cost. At the same time, the support and backing of the local community towards the project was attained, as the repository would exclusively hold the LTCP hazardous waste and would result to a significant upgrading of the overall environmental conditions of the area.

2.2. Repository development

The repository is located at the north-eastern part of the LTCP site under a small hill. The upper layers of the hill are comprised by low strength but impermeable formations as shales, phyllites and graphic schists (Koumantakis et al., 1999), whereas, at the lower part, a layer of competent marble formation (upper marble unit) can be utilized for the development of the facility.

The construction is made within the marble formation between the levels of +12m and +17.5 m (Fig. 3). In general, the geotechnical conditions at the construction level were good and the rockmass can be characterized as "fair to good quality", having RMR values ranging from 52 to 67. The design of the underground repository is made using an underground mining method, namely the room-and-pillar technique (Benardos and Kaliampakos, 2006). Using this particular method a cost-effective construction is achieved and at the same time the maximum utilization of the site's space is attained, if compared with complexes that employing a series of caverns or tunnels. The development of 7-m wide parallel and transverse galleries is made, leaving 7-m wide pillars of the host rock to support the opening, resulting to a pillar factor of safety in the order of 10, while, attaining at the same time an overall mined space utilization of more than 75% (Fig.3.13a). The available space of the facility is around 1,900 m^2, developed out of a total area of 2,475 m^2.

The access works comprise by a 10% steep tunnel, facilitating waste transportation and general access to the repository and by a 35 m deep shaft that will be used for safety reasons and for ventilation purposes (Fig.3.13b).

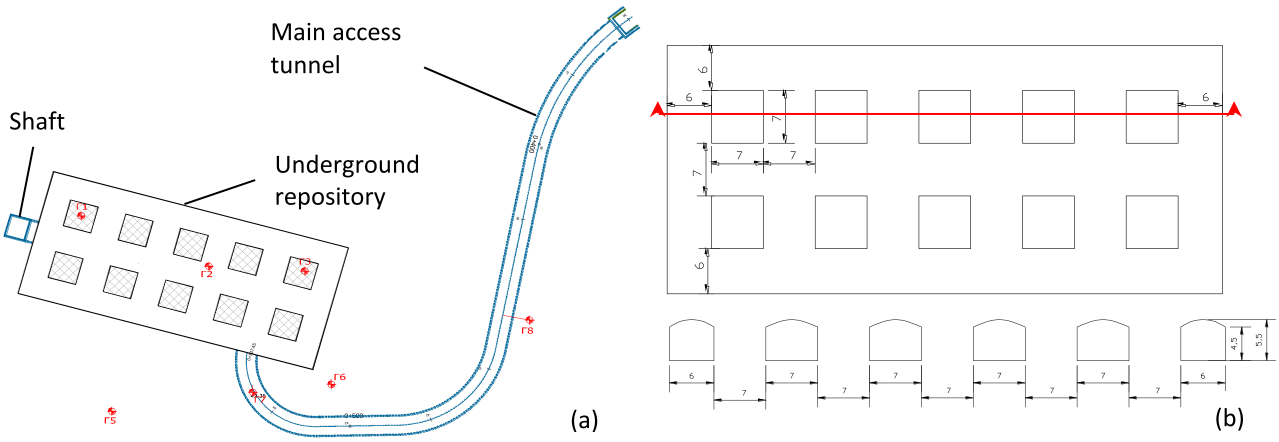


Fig. 3.13. LTCP underground hazardous waste repository (a) general layout of the underground complex, (b) detailed plan of the room and pillar arrangement followed at the main storage area.

The permeability of the host marble formation is an issue that mandates the implementation of an efficient engineering barrier system that would ensure the waste containment and mitigate impacts from possible major accidents to water and ground/soil system. The technical barriers adopted suggest the use of special shotcrete mixtures (ELKEM Microsilica 920 D) for the waterproofing of the roof and sidewalls of the complex, along with the installation of chemically resistant, impermeable, industrial flooring. The design standards, in particular, aimed at attaining a permeability coefficient in the roof and sidewalls in the order of 10^{-9} m/s. In addition, in case of emergency when water infiltration occurs, special pumping units are installed so as to collect any polluted run-offs and, thus, block their diffusion to the water table. These measures, in addition to the special drums that are used for the waste storage, are capable of achieving the safe long-term disposal of the hazardous waste.

The whole project was finished by the end of 2009 and now the repository is fully operational and ready to host the Konofagos' waste (Fig. 3.14).

Fig. 3.14. Photos of the LTCP repository at its present state, ready to hold the hazardous waste.

2.3. Public acceptance

Throughout the whole design and construction period there has been a constant communication between the LTCP administration and the people of the neighboring communities. Many meetings and special presentations were made to the people in order to understand the true nature of the project and its development process. Key issue for attaining public acceptance towards the development of the underground repository was the reassurance that the waste originated from the LTCP area only and no waste from elsewhere were to be stored in this underground repository. This means that the project would finally result to a drastic improvement towards the quality of the communities' living conditions.

2.4. Cost issues

In order to assess the cost benefits from the development of the underground repository, this alternative is directly compared to the only other environmentally sound option available, the export of the waste to underground repositories or special landfills found abroad. The export cost (transportation and disposal cost) varies depending on the waste's characteristics and ranges from 1,500 € to 3,000 € per tn.

The total as-build cost of the LTCP underground repository was 2.8 million €. With its maximum storage capacity in mind, that results to a respective cost of around 560 € per tn, a cost that is at least 3 times lower than the exporting cost. Moreover, as far as feasibility is concerned, things can be even more promising if economies of scale could be reached in other cases if such a development model was to be adopted.

IV. Underground Waste Management Solutions: Future Trends

1. Current perspectives and trends

It is estimated that the usage and adoption of underground waste management applications will be progressively increased in modern cities, affected by both the raised self-consciousness of the public in attaining environmental friendly solutions and the pursue of public authorities and private enterprises to attain low operating costs coupled with high availability degrees. The automated underground vacuum waste transportation (AVAC) is expected to dominate the field in the forthcoming years, especially in cases of densely populated urban areas or in urban expansion projects where the infrastructures can be developed with ease, right from the beginning of the project. For the case of the developing countries, the implementation of stand-alone underground collection scheme seems as a more sensible strategy. This notion is made as the initial investment cost of stationary vacuum systems remains still high. Thus, moving underground utilizing the container collection scheme can be made possible with limited capital expenditure. Yet, such development can benefit communities with reduced operating cost and most importantly with enhanced hygienic and environmental conditions.

The above trends although important in developing, can be further strengthened, especially for the AVAC case, by the development of other systems or strategy options which would allow for a further increase in the efficiency of the underground waste management schemes. Moreover, they would also allow a clear comparison especially in terms of financial appraisal of the underground systems with typical surface waste management schemes. Such issues can reveal the true perspectives of underground solutions for urban waste management and can shift decisions giving the green light for their realization.

2. Future issues to be considered

2.1. Utilization of underground freight transportation

Underground freight transportation (UFT) is presented as one of the possible solutions for transportation and distribution of freight, especially in densely populated areas (Pielage, 2001). As expansion and improvement of existing infrastructure for the various transport modalities are not always possible in these areas, UTF proposes the use of automated cargo vehicles/cargo capsules, moving through underground tunnels or pipelines. More particularly it is a class of unmanned transportation system in which close-fitting capsules or trains of capsules carry freight through tubes between terminals.

This idea is capitalizing on the prior experience of underground networks for the handling of small parcels found in many cities in Europe (London, Paris, Prague, etc.) and in the US (Chicago). All historic systems were pneumatically powered and often referred to as pneumatic capsule pipelines (Vance et al., 1994). Nevertheless, to tackle the drawbacks of such systems (energy consumption, small distance transport) current design approaches utilize either rail transport or more modern systems based on an electromagnetic drive (Fig. 4.1).

The benefits from the development of UTF schemes are quite substantial. For example, a feasibility analysis regarding such an underground freight system for Tokyo (Taniguchi et al., 2001) estimates a reduction in NO_x and CO_2 emissions by 10% and 18% respectively, a reduction of 18% of energy consumption and an increase of 24%in average travel speed in city.

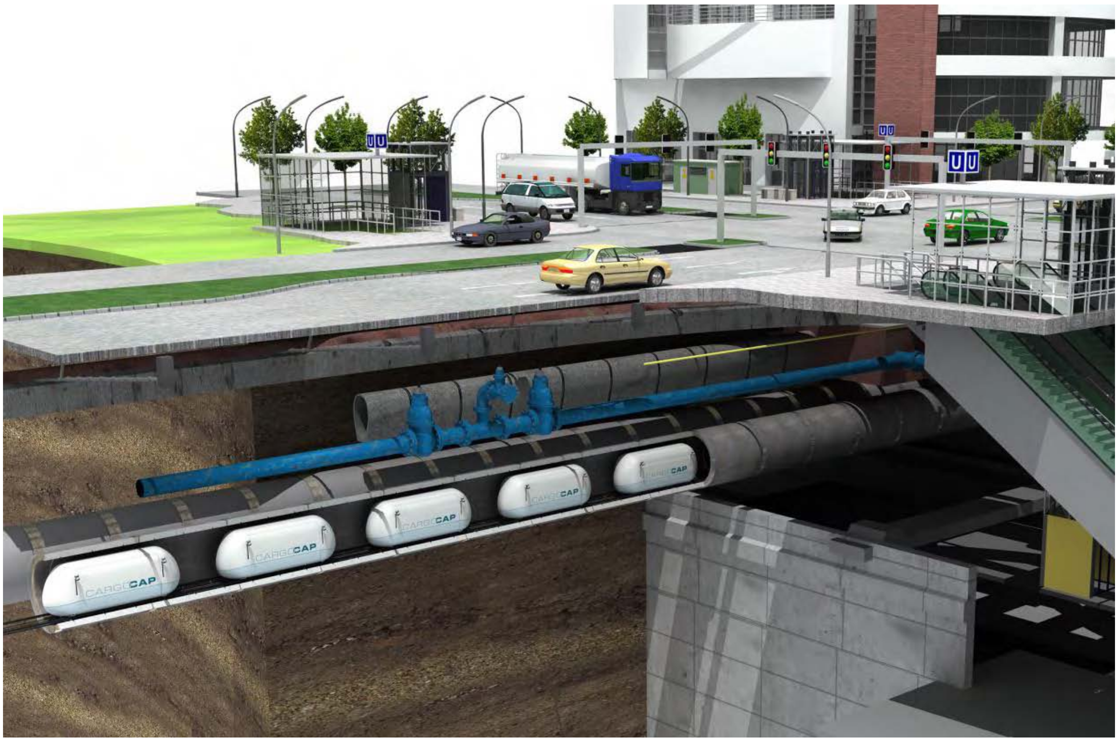


Fig. 4.1. Underground freight transportation using capsules (source: Cargocap GmbH. 2012).

In terms of urban waste management approaches the utilization of UTF can replace current waste transport systems from the AVAC's centralized facility, nowadays relying on truck transportation. In this manner, waste can be transported to recycling facilities or landfill sites without any interference to aboveground city living. This would enable the:

- creation of a highly sophisticated and efficient, automated and autonomous system to operate round the clock for the entire cycle of the waste handling, transportation and management system, from the initial collection points to the final recycling and disposal of wastes.
- elimination or reduction of truck movements for waste transportation, resulting to reduced traffic jams, accidents, noise and air pollution, as well as to reduced energy consumption.
- establishment of increased control over scheduling, faster transportation and lower transportation costs.

2.2. Development of multi-purpose utility tunnels

Utility tunnels are a substantial infrastructure of cities. They are designed to house a number of urban services, such as transmission lines and pipes for district heating, district cooling, electricity and water supply systems, as well as a large number of different cable links (Fig. 4.2).

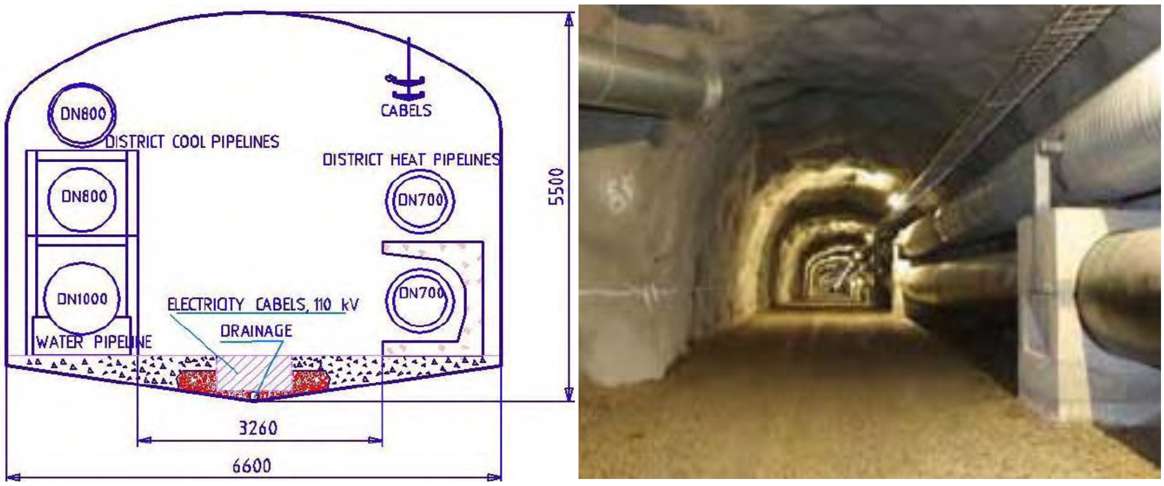


Fig. 4.2. (a) Indicative sketch and (b) inside view of multi-purpose utility tunnel.

The development of utility tunnels in urban areas has a tremendous importance to the level of service offered to technical infrastructure, while at the same time can boost their capacities. The placement of utility networks in tunnels is advantageous because results in a well arranged system, centralized operational control, extended lifetime of utilities and enhanced safety, easy maintenance and repairs. All construction works and repairs are made underground without interference to city environment, traffic, etc. Finally, the corridor design can achieve savings in minimizing the length of the housed services through minimization of curves, while on the same time all expenses can be mutually divided to the service providers (Satola et. al., 2011).

The latter is of major importance in achieving cost-effective solutions, for the operators of underground waste management systems, as by utilizing such infrastructure the major setback in developing automated vacuum waste systems, the initial high capital expenses required, can be greatly controlled. This can enhance the attractiveness of AVAC systems in terms of financial point of view and promote their realization, as they could offer substantial lower collection costs. Of course this is something that requires concession between all stakeholders of services.

2.3. Research on energy consumption reduction and on the collection options for special waste fractions (glass, cardboard)

Increasing the research efforts to further improve the efficiency of AVAC systems can greatly enhance their working envelope as well as their financial bottom-line. Two significant issues are the energy consumption and the collection of special types of waste, and more particularly glass waste.

In this manner, the development on new techniques that could allow for the energy reduction of automated vacuum systems could allow an improvement on the operating cost as well as to the related environmental stresses. Such research efforts are currently underway with the most notable one being the ring-line system developed by MariMatic, using both vacuum and pressure to convey refuse along the pipeline. Main reasons for the lower energy consumption achieved over conventional pneumatic systems is that the ring-line system mainly utilizes the existing air in the network and that the combination of underpressure and overpressure conveys material with less energy than just the underpressure which is used by single-line solutions (Honkio, 2009).

The reliable collection of cardboard boxes and glass through a vacuum waste system has not been resolved yet. Glass bottles typically break inside the collection pipe and at high transport speeds cause erosion to the inside of pipes (especially on the bends) whilst cardboard boxes have a tendency to block the collection pipes. Consequently, the collection of these particular waste fractions is performed with the use of trucks. For the case of glass waste, there are some promising products available which could be incorporated in future systems. For example GLASSVAC offers a processing system for glass waste (Fig. 4.3) capable of efficiently transforming all types of glass into sharp free particles. The system uses implosion, a mechanically induced high speed process that shatters the glass inward on itself without creating any glass shard or sharp edges. It produces a range of fraction sizes from approximately 0.2mm up to 16mm (GLASSVAC, 2012).

Fig. 4.3. (a) GLASSVAC's GP3 Cube and (b) view of the final glass waste after the implosion process.

This technology was first developed to resolve issues for the glass waste of the cruise industry but it has now expanded its range of applications. Similar products could be coupled with automated vacuum waste collection systems and could allow for the management of glass waste in the near future.

2.4. Intensification of pay-as-you-throw (PAYT) and source separation policies

The adoption of modern policies in municipal waste management as the PAYT concept and the source separation principle can further enhance the benefits offered by underground waste management schemes. The PAYT concept provides an incentive to community residents to try to reduce their waste production and increase their recycling capacity. Source separation (segregation of different types of solid waste at the location where they are generated) can reduce the overall management costs as the sorting process stage can be reduced to a great extent, less contamination of recyclables is achieved and thus higher recycling rates and increased revenues are succeeded (WRAP, 2008).

These concepts target different groups; hence, they can come up with the same end result, the decrease of waste management cost to the end-user.

The source separation is one of the inherent advantages of the underground waste collection systems, through the use of multiple inlets (AVAC systems) or storage bins (underground collection points). Nevertheless, only recently have these systems been developed to manage more than 3 fractions of waste, not exploiting their maximum potential, especially for the case of AVAC. The use of multi inlet configurations can assist in achieving a higher degree of source separation and, consequently, all the associated benefits, with only minimal development cost.

The PAYT systems are also introduced to underground waste collection systems; however, their adoption is a community specific approach. Interlinking PAYT and AVAC could result to a more user oriented scheme that could be more attractive to residents, rewarding their recycling efforts and being more socially fair instead of flat-rate taxes. Thus, it could create the setting to ease the transition between traditional waste handling systems and underground automated waste collection ones.

2.5. Assessment of external cost in financial analysis

Taking into account of the environmental benefits for the selection of a solution alternative is (or better saying, should be) a standard procedure for the decision process. The environmental characteristics analyzed often scaled ranging from linguistic expressions and qualitative assessments to explicit results, making hard sometimes to establish a common reference rating system and accurately quantify the consequences of benefits. This, however, is made possible to a great extent through the concept of quantifying environmental changes using monetary values (external cost). At the same time, this option allows to explicitly measure the economic repercussions of a project (or alternatives) and to integrate them in the overall financial analysis.

Especially in alternatives where significant environmental advantages are expected, like the case of underground urban waste management, this perspective could greatly improve the financial comparison. Thus, low cost solutions that have a significant environmental footprint can be disregarded in financial point of view as new and more costly solutions could offer significant environmental gains. For example, with the case of urban waste management in question, alternatives with limited disturbance in the city's man-made and natural environment could be considered as best practices in both the environmental and financial comparison, even though they could possibly require greater implementation cost, over other options. In this manner the latent potential of underground waste management solutions could be fully decoded and the adoption degree of such solutions could be further enhanced.

V. Conclusions

The development of efficient solutions and practices toward the management of urban waste is a key issue in resolving one of the most pressing needs of modern society. Rising waste volumes, increased hygienic and amenity demands as well as environmental considerations impose additional requirements to the waste management system that traditional management schemes are either unable to meet or come across with increased operating cost figures.

The utilization of the subsurface space can provide the setting for the development of infrastructure which is capable of addressing in a more efficient manner the limitations of existing waste management schemes. Surface space is released and made available for other uses, while, on the same time, all processes are taking place underground minimizing their effects in the living environment. Thus, whether this is about municipal solid waste, hazardous waste or even sewage waste streams, efficient solutions can be put into effect.

As far as the urban and municipal waste streams are concerned, the establishment of permanent underground infrastructure for the collection and the management of waste can provide efficient and cost-effective solutions towards that particular goal. Thus, following the example already set by other utilities (e.g. water, sewerage, gas, electricity, etc.) that have developed over time into an underground infrastructure grid, it is expected that the management of various waste streams through underground infrastructure will grow rapidly.

Stand-alone underground or semi-underground collection points offer great advantages over traditional collection bins as they ensure high hygienic standards, superior holding capacity, improved aesthetics as well as limited maintenance requirements. The above features can allow for a considerable increase in the collection interval that can lead to the reduction of the operating cost (transportation, labor, etc.) of the service. Furthermore, the minimal capital expenditure required as well as the flexibility in its siting requirements make such systems ideal for the instant replacement of the wheel containers. Especially for the case of the developing countries, the implementation of stand-alone underground collection scheme seems to be the most sensible strategy.

Automated vacuum (pneumatic) waste collection systems (AVAC) provide an integrated framework for the tacking of the waste handling problem. Not only do they provide temporal storage but also the transportation of waste is taking place through underground pipeline network to a waste collection terminal. By doing so, AVAC systems provide an attractive alternative to conventional vehicle-operated waste collection, as they offer advantages in terms of reduced traffic-related problems, such as noise, accidents, CO_2 emissions, congestion and improve overall safety and hygienic levels. This speeds up the whole garbage collection process, especially at difficult cases as overcrowded urban centers, allowing at the same time a smooth operation of the system even at difficult situations either as a result of severe weather conditions (e.g. storms) or external events (e.g. strikes, protests, etc.).

Major benefit from the usage of AVAC system is the minimized operating cost for the waste handling, 2 to 3 times lower than conventional collection methods. The drawbacks are related to the initial investment required for the setting up of the system which can be substantially be substantially higher (30%-50%) than of a respective surface collection scheme and in the current limitations of the AVAC in handing special waste fractions as cardboard and glass waste as well as WEEE or other bulky waste types. Nevertheless, as indicated in the repost, the reduced operation cost can result to a viable investment scenario, which, in the long run, can counterbalance the negative influence of the high capital expenditure. Furthermore, the new technological developments is expected to expand the applicability envelop of the AVAC system in the near future.

The above can lead to the conclusion that AVAC system is expected to dominate the field of waste collection in the forthcoming years, especially in cases of densely populated urban areas or in urban expansion projects where the infrastructures can be developed with ease, right from the beginning of the project. The cases examples presented in this report as well as many other projects that are currently under design or development process further strengthen the authors' point of view on the matter.

In the case of special and hazardous waste things are even more favorable when assessing the advantages offered by underground repositories. These derive mainly from the fundamental characteristics of underground space; namely the opacity and the natural protection offered, ensuring minimal impacts to the biosphere. Furthermore, when the “on-site” underground disposal is adopted, the benefits from such a solution combine the advantages gained from the underground siting of the repository coupled with the particular opportunities derived by the proximity between the waste producer site and the repository's location.

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