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A framework for a decision support system for municipal solid waste landfill design

Ashley Verge[1] and R Kerry Rowe[2]

Abstract

A decision support system (Landfill Advisor or LFAdvisor) was developed to integrate current knowledge of barrier systems into a computer application to assist in landfill design. The program was developed in Visual Basic and includes an integrated database to store information. LFAdvisor presents the choices available for each liner component (e.g. leachate collection system, geomembrane liner, clay liners) and provides advice on their suitability for different situations related to municipal solid waste landfills (e.g. final cover, base liner, lagoon liner). Unique to LFAdvisor, the service life of each engineered component is estimated based on results from the latest research. LFAdvisor considers the interactions between liner components, operating conditions, and the existing site environment. LFAdvisor can be used in the initial stage of design to give designers a good idea of what liner components will likely be required, while alerting them to issues that are likely to arise. A systems approach is taken to landfill design with the ultimate goal of maximising long-term performance and service life.

Keywords

Decision support system, municipal solid waste, landfill design, barrier systems, computer application, leachate collection system, geomembrane liner, clay liners

Introduction

This article describes a decision support system (DSS) developed to aid in the design of municipal solid waste (MSW) landfills (Landfill Advisor or LFAdvisor). LFAdvisor is intended to act as a guide to landfill design by attempting to replicate the process a designer would follow. It presents available options to the user, perhaps suggesting possibilities or consequences of which the user would otherwise be unaware. The ultimate goal of LFAdvisor is to provide the user with practical information required for a preliminary design quickly, minimising the need to search through the literature. However, should the designer desire further detail, references are provided for all information given by LFAdvisor.

DSSs are computer-based systems used to aid decision-makers in solving problems using some combination of expert systems (ESs), simulation models (SMs), and geographic information systems (GIS). A SM is a computer program used to predict the behaviour of a system. Several SMs exist that are useful in landfill design. GIS have previously been employed in DSSs, particularly for environmental problems where there is a spatial element involved (Adenso-Díaz et al., 2005). Alves et al. (2009) describe a DSS to assess the suitability of sites for landfill construction.

An ES is a computer-based program that contains specialised knowledge pertaining to a particular subject. ESs can be used to solve environmental problems by providing expert advice, and have been used for hazardous waste management (Lukasheh et al., 2001). ESs are valuable because they centralise expertise and make it available to a wider audience. They are a logical way to handle landfill design because of the importance of practical knowledge, the multidisciplinary nature of design, and the limited access to expert opinion in some regions. Reports of ESs that failed to be implemented in practice highlight the problems of attempting to cover too wide of a scope, requiring too many input parameters, and lacking an adequate knowledge base (Basri and Stentiford, 1995).

DSSs have been previously developed to deal with waste management planning (Barlishen and Baetz, 1996). Several ESs have been created to deal with a single component of landfill design, while Basri and Stentiford (1995) combined nine modules related to landfill design. The advancements made by LFAdvisor are described in this article.

LFAdvisor

LFAdvisor consists of an ES containing information necessary for landfill design coupled with several relevant SMs. GIS can be

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employed for landfill site selection; however, this aspect of the design is not included in LFAdvisor, although siting considerations are addressed. The choice of a landfill site is rarely made based on technical suitability alone (e.g. Koerner, 2012).

The primary objective in the development of LFAdvisor was to create a tool that would be implemented by the intended users. A survey of MSW engineers revealed that most decisions in this field are made without the use of any model whatsoever (Barlishen and Baetz, 1996). Thus, a focus was placed on the usefulness and usability of LFAdvisor, two factors that Adenso-Díaz et al. (2005) found to govern whether a DSS will be used in practice. Every effort was made to ensure LFAdvisor was user-friendly, accomplished, in part, by using the familiar Microsoft Windows user interface provided by the Visual Basic programming language. The usefulness of LFAdvisor was addressed by including information gathered from a thorough literature review, including the most recent developments in landfill design.

LFAdvisor builds on a previously developed DSS for landfill design (Çelik et al., 2010) by providing greater detail and considering the important issue of service life. Recommendations from the DSS developed by Çelik et al. (2010) included the elimination of hand calculations, the inclusion of a database containing literature values, and consideration of the leachate collection system (LCS). All of these suggested improvements were incorporated into LFAdvisor. Bioreactor landfills are also considered, which no previous DSS has addressed.

The design of a landfill is not a simple matter; the optimisation of a single component in isolation has the potential to adversely affect the overall performance of the landfill. Proper landfill design requires the adoption of a systems approach (Rowe, 2011) that considers the interactions between the engineered components, the natural environment and the operating conditions for the landfill. As an example, the design of a bioreactor landfill seeks to maximise the generation of gas and accelerate stabilisation of the landfill by increasing the moisture content in the waste (Pichtel, 2005). A conventional MSW landfill liner typically experiences a temperature in the range of 30–40°C, while the primary liner of a bioreactor landfill may have a temperature in the range of 50–60°C owing to increased microbial activity (Rowe, 2011). High temperatures decrease the service life of geosynthetic components (Rowe and Rimal, 2008) and have other negative effects on system performance. LFAdvisor raises technical concerns such as these and, where practical, makes suggestions of ways to mitigate the problem identified so the user may make a more informed decision.

Knowledge base

The information included in LFAdvisor was gathered from textbooks on landfill design and waste management (Koerner, 2012; Pichtel, 2005; Qian et al., 2001; Rowe et al., 2004; Tchobanoglous et al. 1993), technical reports on landfill liner performance (Bonaparte et al., 2002; Mitchell et al., 2007; Needham et al., 2004; Rowe et al. 2001), peer-reviewed journal articles, conference proceedings and landfill regulations from various jurisdictions. The literature review is presented in Verge (2012). Recognising that all of the data required to design a landfill will not always be available, particularly in the initial stage of design, LFAdvisor provides the user with typical values whenever possible so it can still be used as a guide when there is limited detailed information.

Program structure

While several general-purpose DSS 'shell' software programs have been developed (e.g. FRAMES, RAISON), personal communication with the creators revealed that they are not supported on current operating systems and lack the required flexibility for this project. Rather than adopt a system lacking support, LFAdvisor was programmed in Visual Basic, which has previously been used by Adenso-Díaz et al. (2005) for the development of a DSS.

Figure 1 represents the structure of LFAdvisor, covering the complete preliminary design of a MSW landfill. The program begins by requesting information relevant to the landfill being designed (e.g. waste generation rate and available land area). The program then proceeds to the LCS design. Detailed design of the liner components, such as geomembranes (GMs) and clay liners, follows the LCS design. LFAdvisor allows the design of double-lined landfills, which may be selected by the user or suggested by the program. Once the liner design is complete, the characteristics of the attenuation layer may be entered to take account of this extra protection in contaminant transport analysis. Based on the user inputs and calculations performed, LFAdvisor can also display the required inputs into the SM POLLUTE to assess the contaminant transport through the base liner. A cover system may also be designed if desired (not discussed here).

Database

To remain current, a DSS should be easily modifiable so that changes can be implemented in the program as new information becomes available (Barlishen and Baetz, 1996). LFAdvisor handles this issue by using a database to contain information whenever possible. New information can thus be easily added or changed in the database without the need to alter the program code. The database was created using the Structured Query Language Server integrated within Visual Basic to contain relevant information concerning landfill design collected from the literature. The database is used to provide numerical data such as contaminant properties, liner specifications, service life estimates and waste generation. For all data provided, a range of values is given along with a reference to the original data source. As new information becomes available, the database can be updated by the authors and implemented in the original program. Examples of the types of data included in LFAdvisor's database are given in later sections.

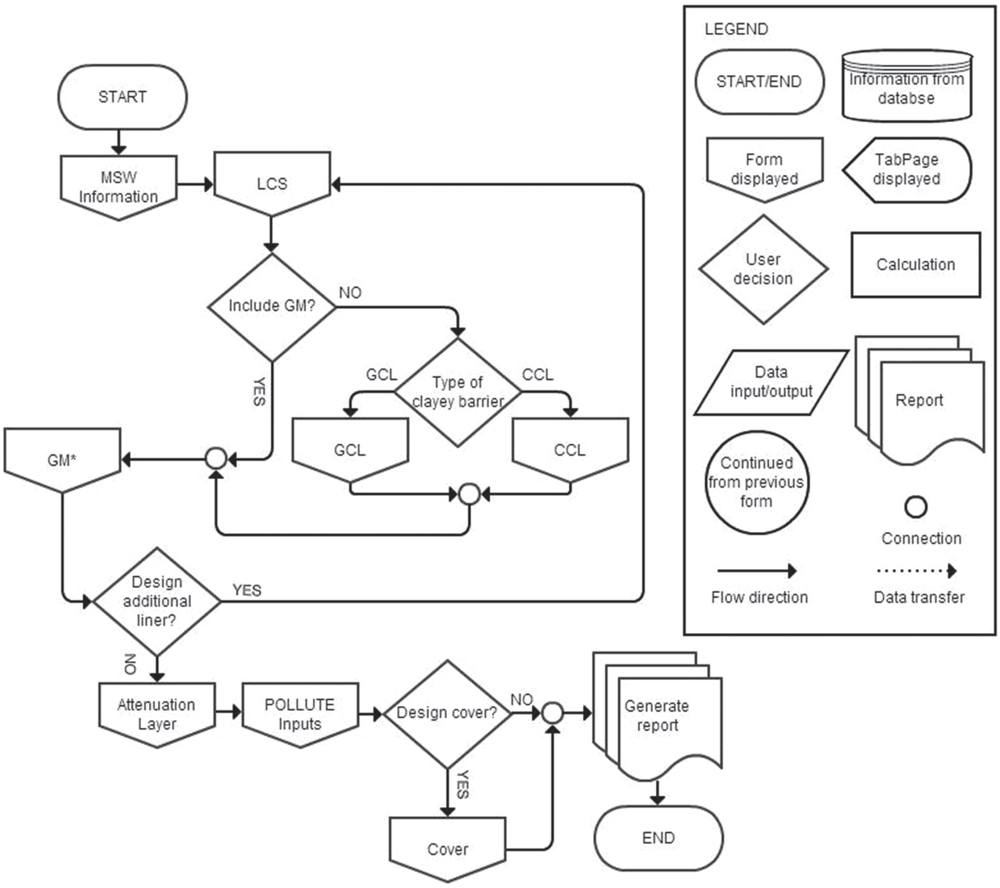

Figure 1. LFAdvisor program structure flow chart and legend. *Form illustrated in Figure 2. MSW: municipal solid waste; LCS: leachate collection system; GM: geomembrane; GCL: geosynthetic clay liner; CCL: compacted clay liner.

User interface

LFAdvisor consists of a series of *forms*, each covering the design of a single component of the landfill design. Each pentagon in Figure 1 represents a form that may be displayed in LFAdvisor depending on user selections. Each form consists of several *TabPages*, each covering a separate, but often interconnected, aspect of the design. Information is shared between TabPages and forms by LFAdvisor as appropriate.

A screenshot of the LFAdvisor user interface is shown in Figure 2, illustrating the *Protection layer* TabPage of the *Geomembrane Barrier* form. This figure illustrates the use of *ToolTips* in LFAdvisor, which are messages displayed to the user when the cursor is hovered over a required input (in this case providing recommended factor of safety values). Figure 2 also demonstrates the use of *LinkLabels* to cite references. Clicking on a LinkLabel opens a separate form containing the references for all the information used in LFAdvisor so the user can find the original source if desired.

Intended use

The intended users of LFAdvisor are engineers involved in the design of MSW landfills. To provide the widest exposure, the program is available free of charge on the Internet at http://www.geoeng.ca/BarrierSystems.html.

Limitations

LFAdvisor contains many correlations and 'typical' parameters and is meant as a preliminary design tool. The information contained in LFAdvisor is for guidance only; it is not to be regarded as complete in itself and should therefore not be used without independent examination and verification of its suitability for any particular project.

LFAdvisor functionality

MSW information. Figure 3 is an enlargement of the *MSW Information* form depicted in Figure 1. LFAdvisor allows the selection of a regulatory regime to be followed and will remember this choice, making suggestions consistent with these regulations for the remainder of the program. It is also possible to use LFAdvisor without adhering to any of the considered regulatory systems. This form requests the site coordinates, which are used to obtain the average annual precipitation predicted at the proposed landfill site. Alternatively, a known value of precipitation may be manually entered by the user. A percentage of the annual precipitation is then used to estimate the infiltration into the waste. The

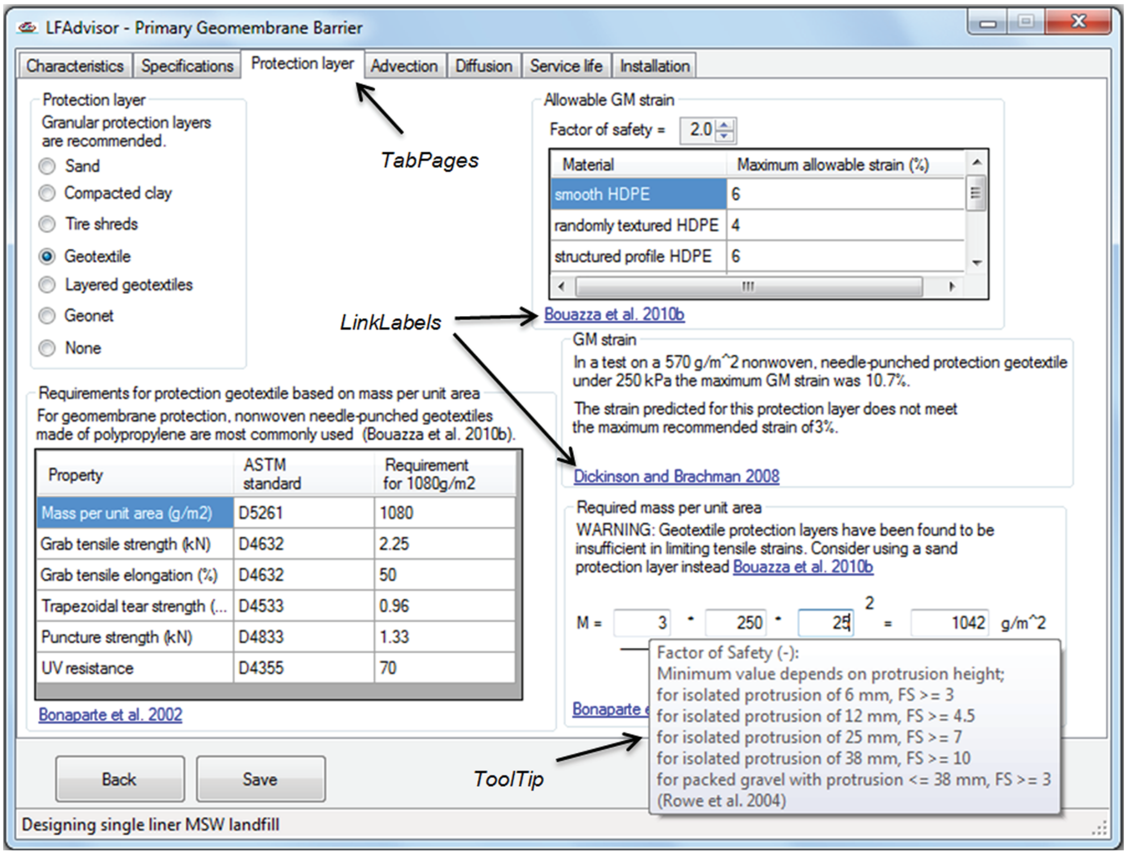

Figure 2. Example of LFAdvisor user interface.

user is alerted that this is a crude approximation and that a SM such as the Hydrologic Evaluation of Landfill Performance model (Schroeder et al., 1994) should be used in a final design.

The amount of landfill gas generated can be estimated based on the waste composition. The database includes reported waste composition and diversion rates from regions worldwide. LFAdvisor calculates a representative chemical formula in the form $C_aH_bO_cN_d$ for the waste based on typical elemental composition of waste constituents (Pichtel, 2005; Tchobanoglous et al., 1993). The total theoretical gas generation is reported, as well as the expected gas composition.

The database contains waste generation rates for European countries (EEA, 2011), Canada (Statistics Canada, 2011), and the USA (EPA, 2011). The user may enter data such as population and desired landfill lifespan to calculate the required landfill capacity or simply enter an estimated waste volume. The required landfill volume is estimated based on the waste mass, a user-specified waste density, and an assumed ratio of cover soil to waste volume. Several possible options are provided for daily cover materials, including the traditional soil cover as well as newer alternatives, such as foam and tyre shreds. The user is also aided in deciding on the landfill dimensions, including consideration of a buffer zone.

For landfills designed to contain a large amount of waste, contaminant transport modelling may demonstrate that a double liner is required to reduce contamination to an acceptable level. LFAdvisor calculates the waste loading of the site by dividing the estimated volume of the landfill by the specified landfill footprint. The waste loading can then be compared to maximum waste loadings defined by the Ontario, Canada, regulations to suggest the use of a single or double liner (MoE, 1998):

$$G_s = 159.9*[\mathrm{Cl}] + 99205 \qquad (1)$$

$$G_d = 356.51*\left[\mathrm{Cl}\right] + 292167 \qquad (2)$$

where G_s ($m^3\ ha^{-1}$) represents the maximum waste loading for a single liner, G_d ($m^3\ ha^{-1}$) is the maximum waste loading for a double liner and [Cl] (mgL^{-1}) is the background chloride concentration in the aquifer. If the site waste loading is less than G_s, a single generic design is suitable. If it is greater than G_s but less than G_d, a double liner is required unless it can be demonstrated by modelling that the impacts would be acceptable as defined in Ontario regulations (MoE, 1998). If the waste loading is greater than G_d, neither generic design is appropriate for the landfill conditions and a performance-based design is necessary.

Leachate collection system design. The *Leachate Collection System* form (Figure 4) allows the user to specify whether a bioreactor landfill will be designed. The consequences of this choice are considered for the remainder of the design.

The user may select the drainage material from a range of choices including gravel, sand, tyre shreds and geocomposite drainage.

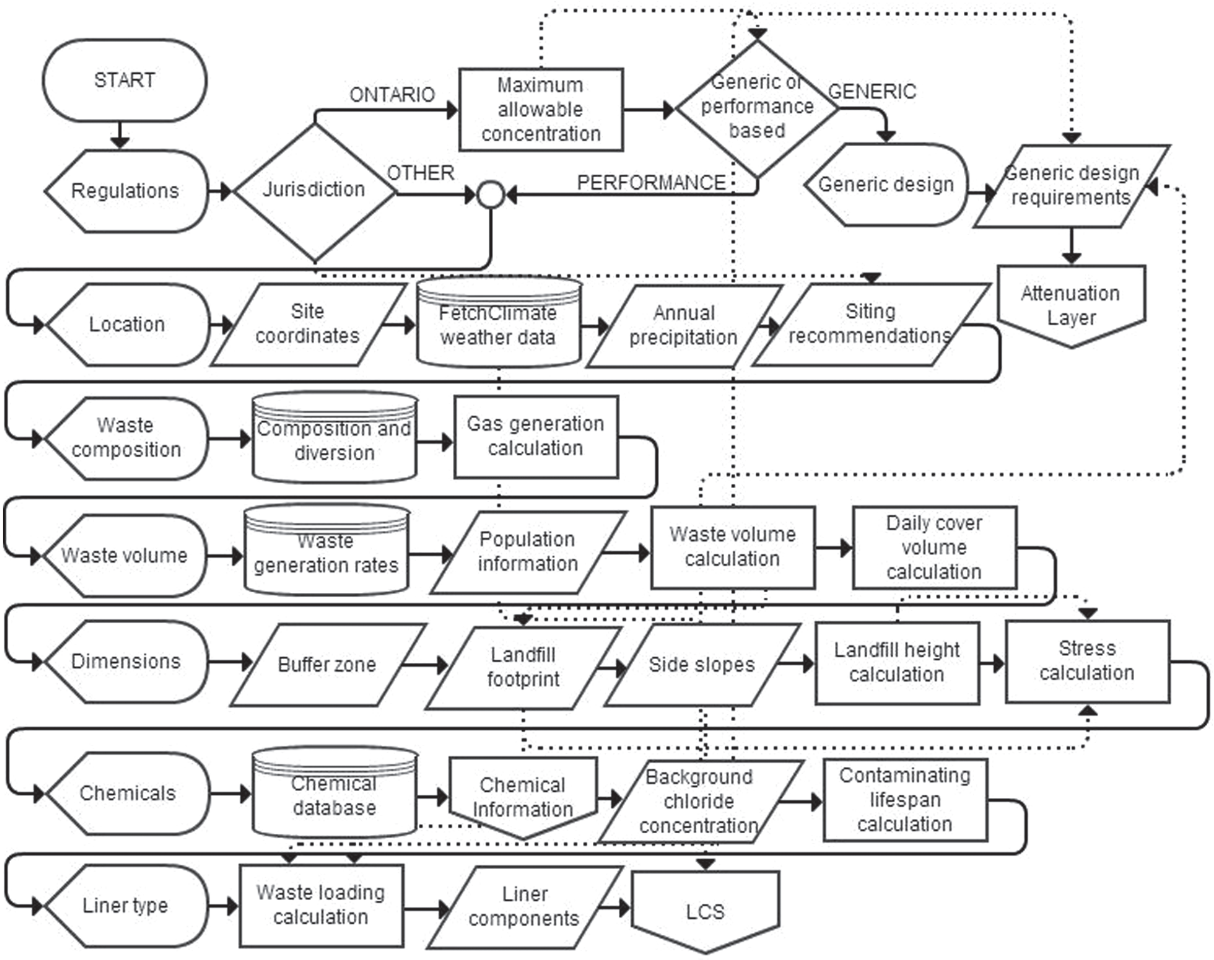

Figure 3. LFAdvisor municipal solid waste information form structure. LCS: leachate collection system.

LFAdvisor recommends a non-woven, needle-punched geotextile filter, as they have been shown to extend the service life of the drainage layer (McIsaac and Rowe 2006; Rowe and Yu 2013a; Yu 2012).

The required spacing of the perforated collector pipes is calculated using an equation presented in Rowe et al. (2004) to ensure an allowable height of leachate mounding is expected. The LCS pipes can be designed based on recommended sizes and perforation configurations from the literature. Pipe stability is assessed with the dimension ratio calculation (Rowe et al. 2004).

The deflection of the pipes due to the weight of the waste can be calculated based on the method presented by Moore (2001). The required inputs are vertical stress on the pipes (calculated by LFAdvisor if the height of waste was specified), Poisson's ratio of the material surrounding the pipe, mean pipe diameter, and Young's modulus of the pipe (a representative value is provided depending on the material selected). The user is also notified that the result should be multiplied by a factor to account for contact with coarse gravel and high temperatures.

LFAdvisor uses a simplified version of the SM BioClog presented by Rowe and Yu (2013b) to predict the service life of the LCS. The model permits linearly decreasing concentrations of chemical oxygen demand, total suspended solids and calcium in the leachate from time t_1 to t_2. The rate of infiltration into the landfill can also be assumed to change after time t_2 owing to the installation of a final cover. LFAdvisor uses an iterative procedure to compute the expected LCS service life.

The required flow rate of a geonet is calculated from the leachate inflow rate and the drainage length of the geonet (Koerner, 2012). If laboratory flow rate results are available, LFAdvisor calculates the allowable flow rate by taking into account reduction factors (Koerner, 2012) stored in the database. A factor of safety can then be calculated from the ratio of the allowable flow rate to the required flow rate. If laboratory data are not available, LFAdvisor can calculate the laboratory flow rate that would be necessary to achieve any desired factor of safety.

The user is aided in estimating a likely liner temperature based on the chosen configuration and site conditions using temperature ranges reported by various researchers. Following completion of the LCS design, LFAdvisor will proceed to the *Compacted Clay Liner* form or the *Geosynthetic Clay Liner* form, depending on the selection made by the user.

Compacted clay liner design. The *Compacted Clay Liner* form begins by requesting the predominant clay mineral type

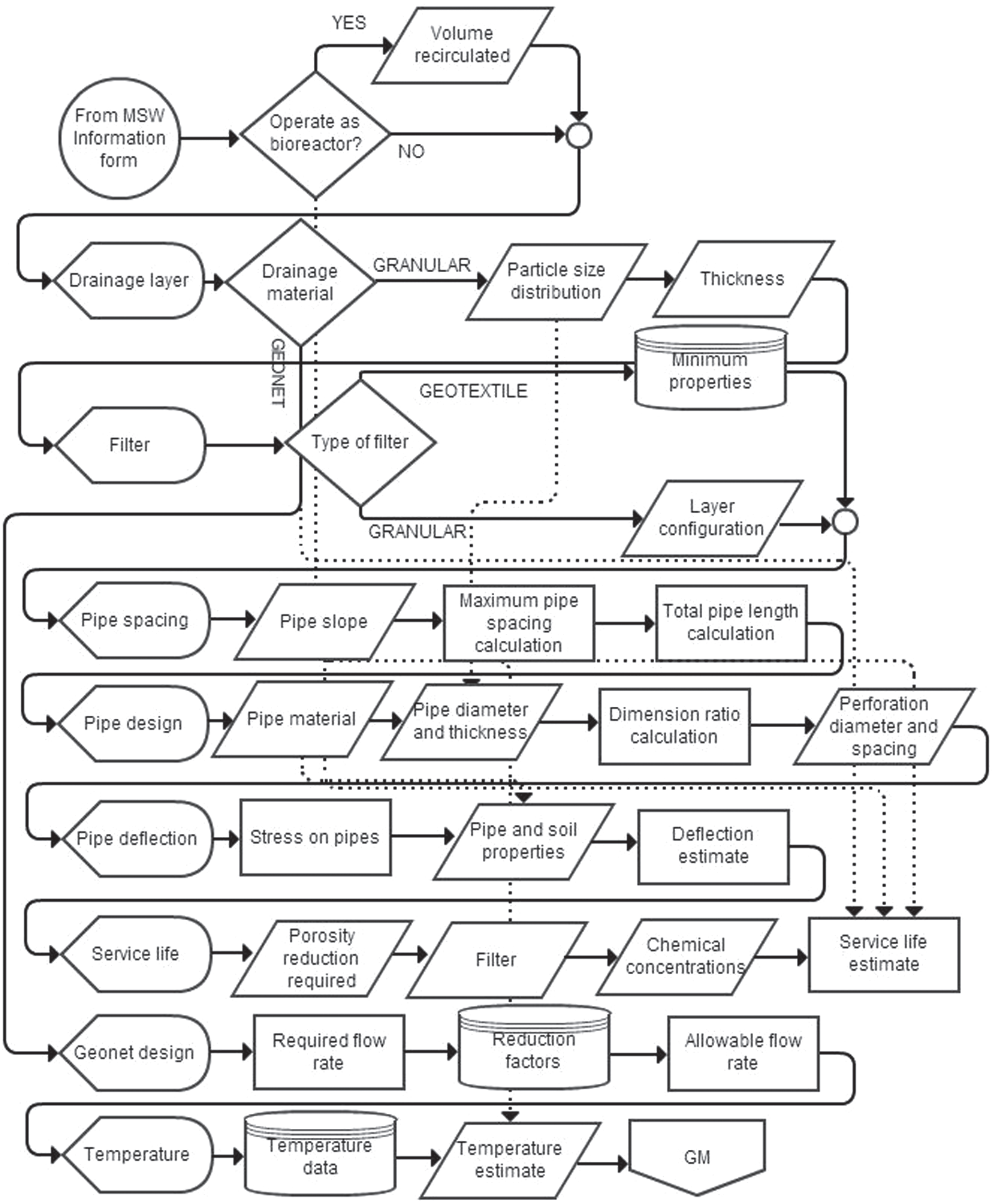

Figure 4. LFAdvisor *Leachate Collection System* form structure. MSW: municipal solid waste; GM: geomembrane.

of the proposed liner material. LFAdvisor will indicate whether the chosen clay is suitable for use as a compacted clay liner (CCL) depending on typical characteristics of various clay types stored in the database. This is based on the potential for increase in hydraulic conductivity owing to clay/leachate incompatibility, which can occur when clay minerals are exposed to certain chemicals (Mitchell et al., 2007). The Atterberg limits can also be entered to calculate the activity and plasticity index of the clay. These values are compared to the recommended range for clay used as a CCL and warnings are given when appropriate. The particle size distribution can also be entered and compared to recommendations from the selected regulatory regime.

LFAdvisor provides suggestions to prevent desiccation of the CCL. If the liner configuration or clay type selected are prone to desiccation, the user will be alerted to this fact and possible mitigation strategies will be given. For example, if the calculated plasticity index was > 30%, a warning appears to alert the user

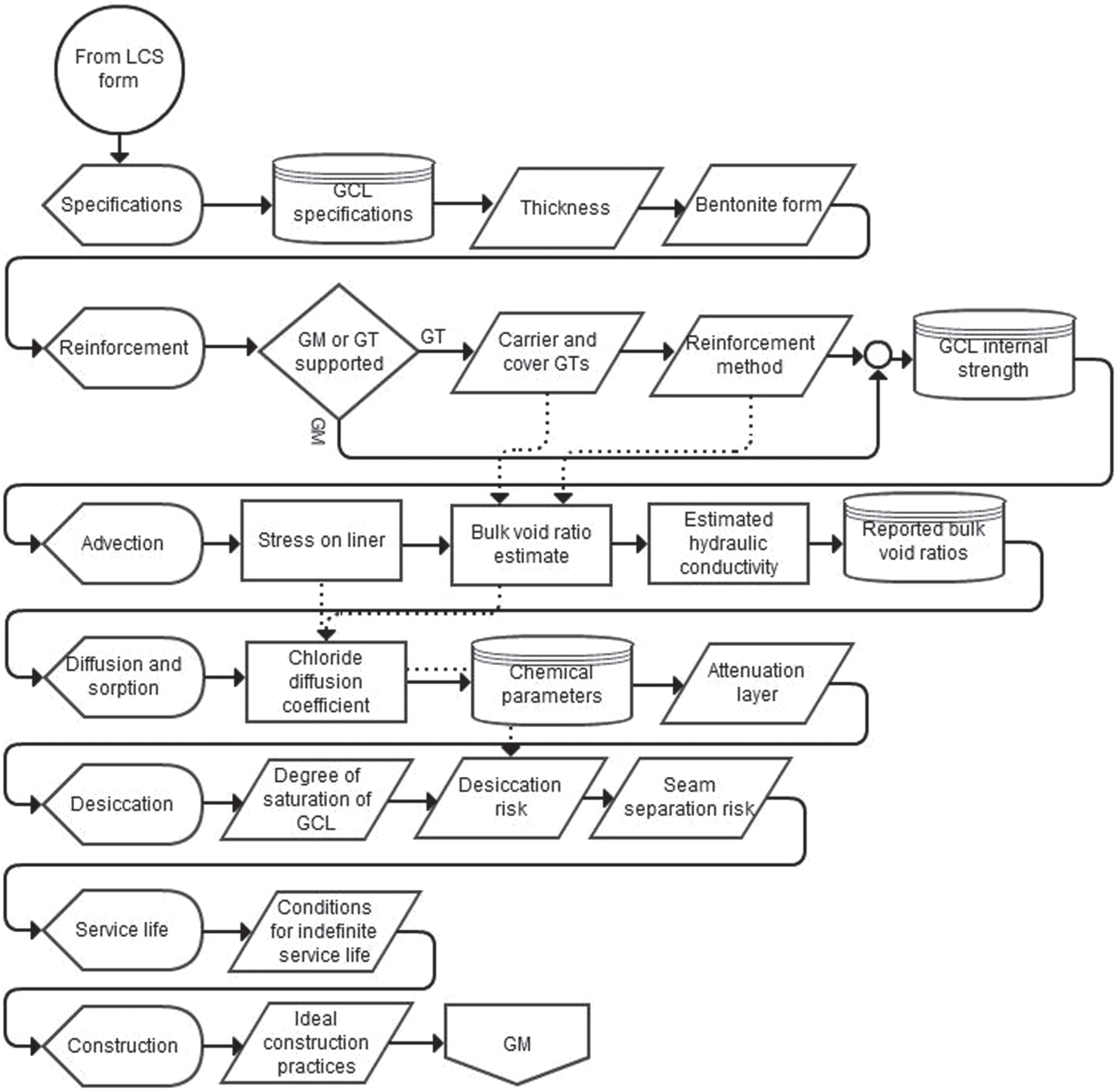

Figure 5. LFAdvisor *Geosynthetic Clay Liner* form structure. LCS: leachate collection system; GCL: geosynthetic clay liner; GM: geomembrane; GT: geotextile.

that clods are likely to form in these conditions, which can lead to shrinkage and drying after compaction (Rowe et al., 2004). The importance of quickly covering the CCL is also emphasised.

Geosynthetic clay liner design. The *Geosynthetic Clay Liner* form (Figure 5) begins by presenting recommended geosynthetic clay liner (GCL) specifications. The expected internal strength of the GCL is given based on the geotextile type and reinforcement method selected. Depending on the chosen type of GCL and the overburden pressure on the liner, an estimate of GCL bulk void ratio can be made. This estimated value is used to predict the hydraulic conductivity of the GCL from empirical relationships reported by Rowe et al. (2004).

LFAdvisor displays the diffusion and distribution coefficients reported for GCLs. A correlation between the bulk void ratio and the diffusion coefficient of chloride is also presented. The user is notified that while the diffusion coefficients for GCLs are low, the thinness of GCLs relative to CCLs increases the diffusive flux unless a sufficient thickness of attenuation layer underlies the GCL.

LFAdvisor assesses the potential for the GCL to form desiccation cracks, which increases the hydraulic conductivity and the advective flux of contaminants, using results from the SM DESICCATE based on the expected temperature, stress level, and degree of saturation of the GCL when stress is applied. Measures to decrease the likelihood of desiccation are discussed. LFAdvisor outlines the conditions under which GCLs can be expected to have a service life of hundreds to thousands of years. Situations that will decrease the service life of a GCL include bentonite loss or thinning, seam separation, erosion of bentonite from the GCL and desiccation (Rowe et al., 2004). LFAdvisor aims to provide information to help prevent these issues throughout the design process.

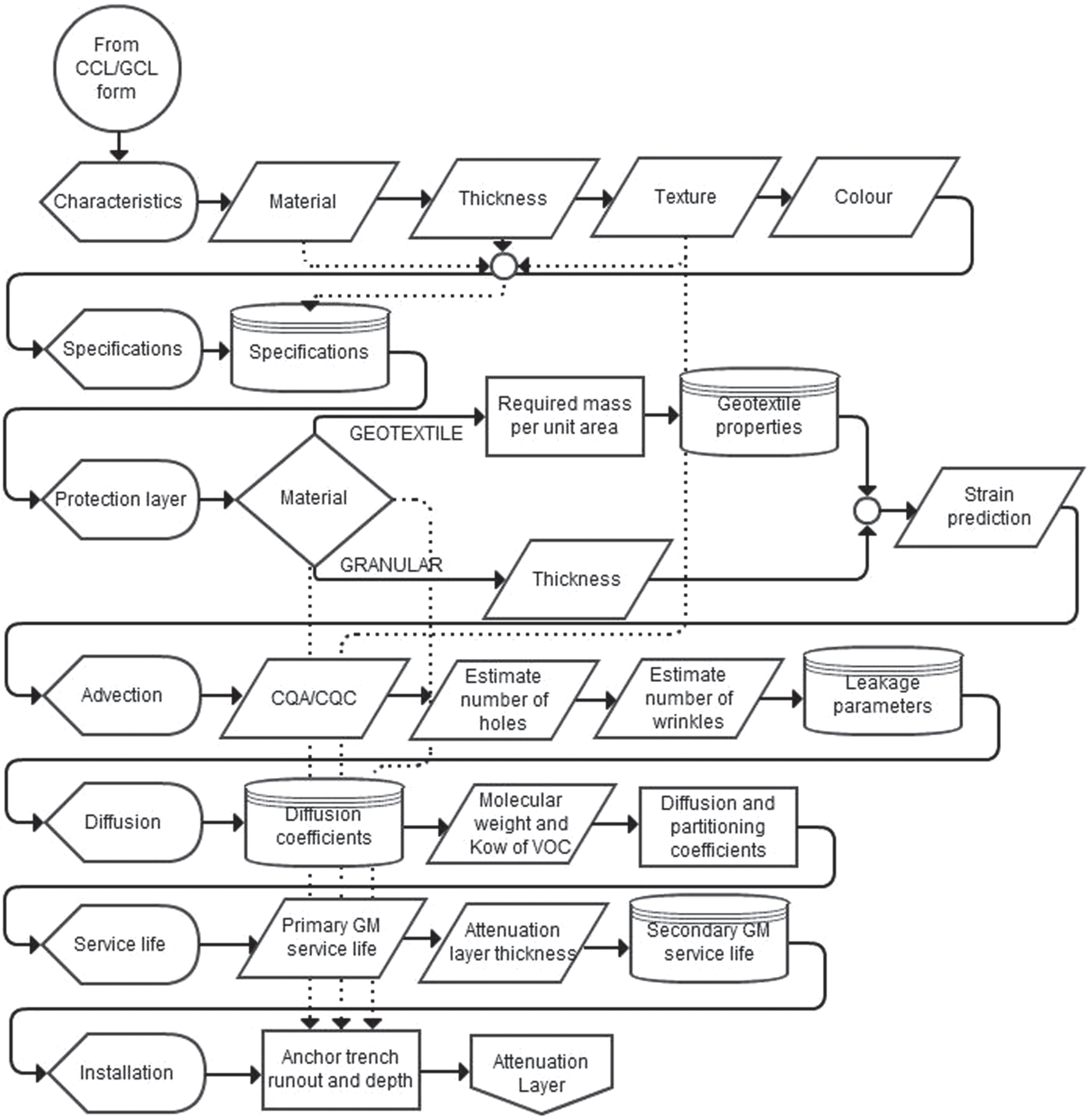

Figure 6. LFAdvisor *Geomembrane Barrier* form structure. CCL: compacted clay liner; GCL: geosynthetic clay liner; CQA/CQC: construction quality assurance/construction quality control; VOC: volatile organic compound; GM: geomembrane.

GM design. The *Geomembrane Barrier* form (Figure 6) allows the selection of various GM properties, such as material, thickness and texture. High-density polyethylene is recommended for the base liner of landfills, while linear low-density polyethylene is more commonly used for landfill covers (Needham et al., 2004). Based on these selections, the recommended specifications will be displayed using data stored in the internal database.

LFAdvisor recommends a soil protection layer instead of the traditional geotextile based on recent research indicating that geotextiles are insufficient in limiting tensile strains in the GM. If a geotextile is selected, LFAdvisor calculates the required mass per unit area based on the method presented by Koerner (2012). The required properties based on the calculated mass per unit area are displayed from the database. Based on tests reported by Dickinson and Brachman (2008) on a GM/GCL composite liner, the expected strain is reported for the protection layer selected by the user. If the strain exceeds the allowable value of the GM, the user can choose an alternate protection material that offers better strain resistance.

The user can select the level of construction quality assurance (CQA) of the liner that is expected. A greater number of possible errors or problematic conditions can be expected to remain undetected and unrepaired if a lower level of CQA is performed. The interface transmissivity of the liner depends on the clay type, with GM/GCL interfaces observed to leak less than GM/CCL interfaces (Rowe, 2011). Based on the CQA level selected, the inputs into the POLLUTE software required to quantify leakage for the composite liner selected are displayed to the user.

LCS pipe design

HDPE was selected for the LCS pipes. The pipes were designed with an outer diameter of 300 mm and a thickness of 30 mm for a corresponding dimension ratio (DR) of 10 which meets the maximum recommended DR of 11 and is acceptable for use (Rowe et al. 2004).

LCS pipe deflection

The deflection ratio of the LCS pipes is estimated to be between 1.25 and 1.56%. This design is likely to meet the limit of 5% deflection (Rowe et al. 2004). This estimate is based on a vertical stress of 160 kPa, Poisson's ratio of the pipe of 0.3, mean pipe diameter of 0.270 m, and Young's modulus of the pipe of 150000 kPa. For coarse gravel, this result should be multiplied by a factor depending on the site conditions. For 50 mm gravel, an appropriate factor may be 1.3 to 2.0 (Rowe et al. 2004). This method does not consider the effect of high temperature on deflection (Koerner 2012).

LCS pipe service life

The estimated service life of the LCS is 89 years. This estimate assumes a nonwoven geotextile is used as a filter. The estimate is based on a drainage layer thickness of 0.3 m, drainage length of 25 m, porosity reduction required to cause clogging of 0.2, and clog density of 1500 kg/m^3. Leachate concentrations are assumed to be constant (COD = 62.1 kg/m^3, calcium = 4.0 kg/m^3, TSS = 6.0 kg/m^3) until 10.7 years, when they linearly decrease (COD = 7.2 kg/m^3, calcium = 0.2 kg/m^3, TSS = 2.0 kg/m^3) by 16.7 years. The infiltration rate is assumed to be 0.2 m/a until 16.7 years, after which time the infiltration is 0.15 m/a (Yu 2012).

Figure 7. Excerpt from example report generated by LFAdvisor.

Table 1. Suggested POLLUTE parameters for leakage through composite liners.

Parameter	Good CQA	Limited CQA
Hole in wrinkle frequency (holes ha^{-1})	2.5	16
Wrinkle width (m)	0.2	0.3
Wrinkle spacing (m)	40	6
Wrinkle length (m ha^{-1})	100	100
Hole radius (m)	0.001	0.05
GM/CCL transmissivity (m^{2}s^{-1})	1.6×10^{-8}	1×10^{-7}
GM/GCL transmissivity (m^{2}s^{-1})	3×10^{-11}	1×10^{-10}
Conductivity (ms^{-1})	Hydraulic conductivity of drainage layer	

CQA: construction quality assurance; GM: geomembrane; CCL: compacted clay liner; GCL: geosynthetic clay liner.

Although the POLLUTE software was written before the concept of interconnected wrinkle length was established, the values in Table 1 were developed to give numerically equivalent results.

LFAdvisor displays the diffusion and partitioning coefficients through the GM. Additionally, LFAdvisor incorporates empirical relations reported by Sangam and Rowe (2001) to estimate the diffusion, partitioning and permeability coefficients of volatile organic compounds.

LFAdvisor presents an estimate of the primary GM service life based on the expected temperature of the liner with predictions given by Rowe (2007). The service life of the secondary GM, if included, is estimated based on results from Rowe and Hoor (2009). This estimate takes account of the liner configuration specified by the user and the temperature of the primary GM. If the estimated service life is insufficient, LFAdvisor suggests measures that could be taken to increase the service life and what gains could be expected. There is considerable ongoing research into the service life of geomembranes and the estimates of geomembrane service life may need to be revised as that information comes available.

LFAdvisor allows the required anchor trench runout and depth to be calculated based on equations presented by Koerner (2012). The calculation requires the allowable stress in the GM, which must be obtained with laboratory tests; however, the typical range of values is provided. Based on the selections made previously, LFAdvisor accesses the database to provide literature values for interface friction with the GM.

Attenuation layer information. The *Attenuation Layer* form gathers information pertaining to the existing soil at the landfill site. A soil balance on requirements for daily cover, CCL construction and the final cover can be performed to estimate the required excavation volume. Simple borehole data can be entered as a preliminary representation of the subgrade conditions. LFAdvisor calculates the factor of safety against blowout for the specified excavation depth, and depressurisation of the aquifer is recommended if blowout is a concern.

The internal database stores reported interface friction values for various landfill component combinations. All of the interfaces are identified from the configuration selected by the user and the corresponding friction values are presented. From this, the user can evaluate what is likely to be the weakest interface to be analysed in detail. LFAdvisor calculates the factor of safety for slope stability using limit equilibrium analysis.

The harmonic mean hydraulic conductivity is also calculated to account for all of the soil liners designed, as well as the attenuation layer specified. This hydraulic conductivity is then used to estimate the Darcy flux, or leakage, through the landfill liner system.

Conclusion

This article outlined the structure of a decision support system for the preliminary design of a MSW landfill, considering the possible inclusion of a LCS, GM, CCL, GCL and attenuation layer. Relevant literature from numerous sources has been consolidated in LFAdvisor to facilitate the design process. It provides suggestions on the necessary liner type and presents the issues that may arise depending on the interactions between the selected components, operating conditions and the existing environment of the proposed site. LFAdvisor could be used by landfill designers to take a systems approach to the design process as a way to maximise long-term performance and service life.

The output of LFAdvisor is a report detailing all of the information that has been entered, results of service life analyses, as well as any assumptions made by LFAdvisor or conditions on the results. The report is generated as a PDF document that can be saved or printed for future reference. Figure 7 provides a short excerpt from a report generated by LFAdvisor. This part of the report provides the results presented previously on several TabPages of the *Leachate Collection System* form. The inputs provided by the user are reproduced along with analysis results (e.g. the service life of the LCS). Where recommendations for parameters exist, an assessment is made of the computed results. Citations are provided where appropriate, with the complete reference list provided at the end of the report.

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Declaration of conflicting interests

The authors declare that there is no conflict of interest.

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