CAPACITY EXPANSION MANAGEMENT OF LANDFILL GAS EXTRACTION PROJECTS

by

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Abstract

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The aim of this paper is to address the need for effective capacity expansion management in the landfill gas extraction environment. Landfills expand as waste is deposited over time, which creates the need for the capacity expansion of Landfill Gas Extraction Projects (LFGEPs).

LFGEPs start off small and expand throughout the lifetime of the project with the addition of more gas wells to extract the maximum quantity of Landfill Gas (LFG). The extracted LFG is combusted in generators to produce electricity. Extracted LFG, that cannot be used to generate electricity because of the limited number of generators, is flared. This results in decreased electricity production and loss of income for the project.

Capacity expansion in LFGEPs is made up of two parts. Firstly it should be determined when a specific landfill cell should be developed and which type of gas well (vertical gas well or horizontal gas collector) should be installed to maximise the net income for this cell. The cell development sequence is of critical importance as the extracted LFG flow rate should match the electricity generating capacity of the plant throughout the life time of the project to maximise the Return On Investment (ROI). An integer programming approach is followed in this study to develop a cell development sequence plan that guarantees a constant LFG flow to the generators.

Secondly, the optimal electricity generating capacity is calculated to accommodate the extracted LFG. LFGEPs generate income by selling the generated electricity to Eskom and by trading in Certified Emission Reductions (CERs). The LFG flow rate fluctuate as gas wells are installed in newly developed landfill cells. Every cell contains different types of waste that is at different stages of decomposition. This creates variation in the flow rate of the extracted LFG. The generators' capacity must be adapted to handle such a variation. The news vendor problem approach is used to calculate the number of generators needed at every stage of the project.

The capacity expansion of the two areas must match through the whole life-cycle of the project to maximise the quantity of LFG used for electricity production. This paper describes the procedure to achieve this with the techniques described above. The two methods are interlinked as one model's output will be used as input to the other model and vice versa. This forms a continuous cycle throughout the life time of the project.

The Weltevreden landfill is used as a real-world case. The results from the two models described above are compared to the current capacity expansion plans of the landfill. Results are promising as the modeled capacity expansion plan showed an increase in ROI of 4% compared to the current plan.

Keywords: Landfill Gas Extraction, Carbon Emission Reductions, Clean development mechanism, Integer Programming, News Vendor Problem.

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List of Acronyms

GHG	Greenhouse Gas
CH_4	Methane
CER	Certified Emission Reduction
CDM	Clean Development Mechanism
LFG	Landfill Gas
ROI	Return On Investment
kWh	kilowatt hour
GWh	Giga Watt hour
CO_2	Carbon Dioxide
H_2	Hydrogen
DDP	Deterministic Dynamic Programming
PDP	Probabilistic Dynamic Programming
NPV	Net Present Value
CEP	Capacity Expansion Problem
CEM	Capacity Expansion Model
LFGEP	Landfill Gas Extraction Project
EOQ	Economic Order Quantity
IP	Integer Programming
DME	Department of Minerals and Energy
EMM	Ehurhuleni Metropolitan Municipality
UNFCCC	United Nations Framework Convention on Climate Change

Chapter 1

Introduction and background

1.1 The landfill site

Landfill Gas (LFG) is produced by the biological breakdown of organic matter in the absence of oxygen. Figure 1.1 illustrates the production of LFG over time. The LFG quantity (in $m^3/hour$) increases rapidly and then reaches a peak after which it gradually decreases to zero. The collectable LFG quantity is less than the LFG produced in the landfill because of leakage through the landfill capping layer as well as losses in the LFG extraction process.

The landfill substrates contain methanogenic bacteria (*Methanosarcina and Methanosaeta*) that obtain their energy from the conversion of a limited number of substrates to LFG. The major substrates are H_2, CO_2, formate, and acetate (Whitman et al., 1992). All of these substrates are converted stoichiometrically to CH_4. LFG is made up of 40 - 60 % CH_4, with the remainder being mostly other hydrocarbons (ethane, propane, butane, etc.) as well as some nitrogen, oxygen, water, carbon dioxide, sulfur and various contaminants as seen in Figure 1.2. The various phases that the LFG production process go through depend on factors such as humidity, temperature and atmospheric pressure. Nitrogen makes up most of the LFG in the first phase of the conversion process when oxygen is still present in the landfill. Carbon dioxide rapidly increases in the anaerobic phases with the final composition of LFG being mainly methane and carbon dioxide.

Landfills generally receive waste over a period of twenty to thirty years. This means that waste in an older inactive cell of the landfill could be in the final phase of LFG production while a new active cell will only be starting to produce LFG. The four phases as described by Berger and Mann (2001) are:

Phase I Aerobic bacteria consume oxygen present in the landfill as well as the proteins, lipids and complex carbohydrates found in organic waste. The byproduct of this process is carbon dioxide which lasts for days or months depending on the waste content .

Phase II After oxygen present in the landfill cell has been consumed by the aerobic bacteria the compounds created in phase one are converted into methanol, ethanol, acetic and lactic acid in an anaerobic process. This phase lasts a week at most but will return to phase one if the process is disturbed or oxygen is introduced into the landfill.

Phase III Anaerobic bacteria convert the acids produced in phase two to acetate which is an organic acid. Methane producing bacteria and the acid producing bacteria have a mutual relationship; the acid producing bacteria form acids which is the methane producing bacteria's main energy source. By consuming the acetate and carbon dioxide the methanogenic bacteria help keep a neutral pH throughout the landfill. The acid producing bacteria cannot survive in a acidic environment.

Phase IV Phase four begins when LFG is produced at a stable rate. LFG is emitted for between twenty and fifty years after the cell initially started receiving waste.

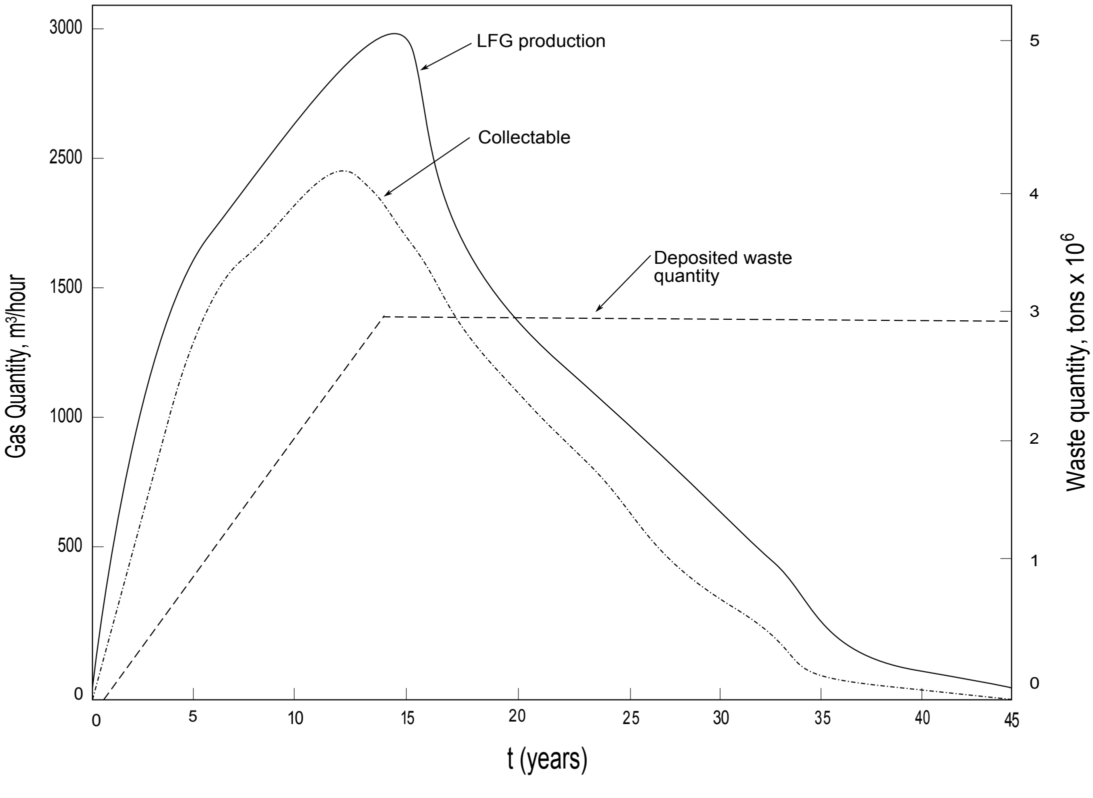


Figure 1.1: Landfill gas production over the course of time

(Koch, 2001)

1.2 Landfill gas migration

Kjeldsen and Fischer (1995) states that LFG migrates through the landfill through two main processes; firstly through diffusion and secondly through pressure gradients. As the landfill gas is

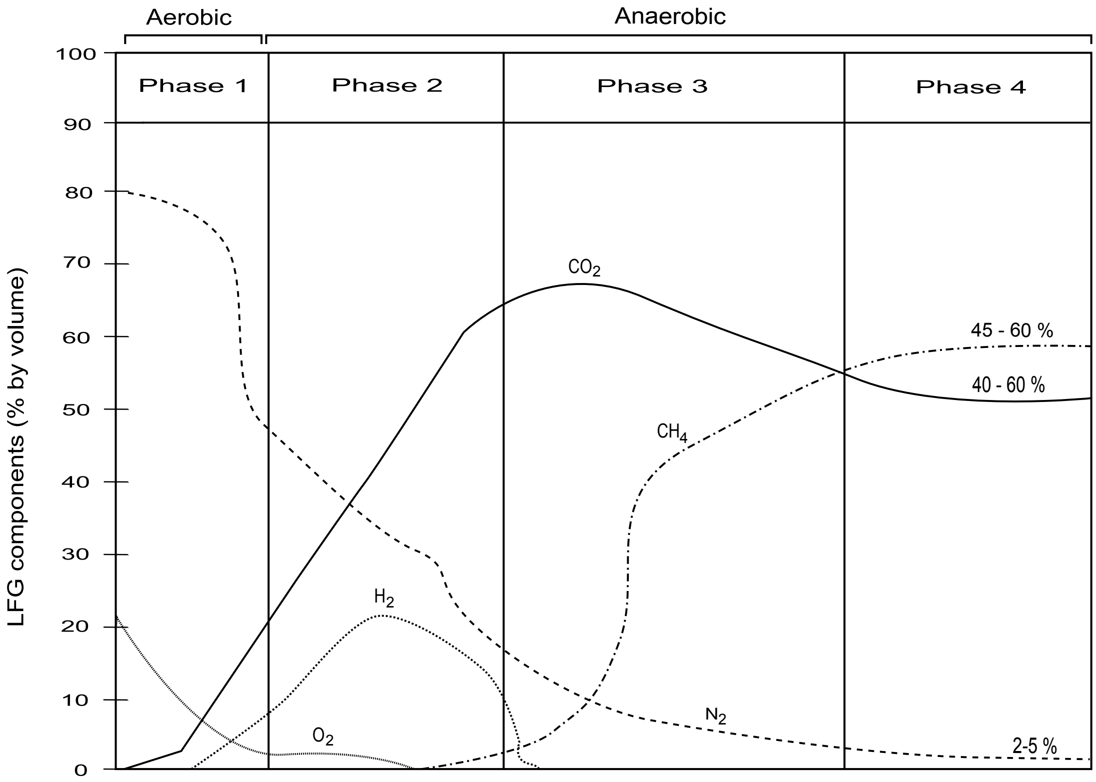


Figure 1.2: The four phases of bacterial decomposition of landfill waste (Berger and Mann, 2001)

produced by the anaerobic bacteria, the residual pressure builds up inside the landfill. The LFG moves from high to low pressure until it finds an exit point and escapes into the atmosphere .

LFG contains CH_4 which is a highly flammable gas and can cause harmful explosions if not dealt with properly (Williams and Aitkenhead, 1991). Besides the obvious danger of explosions, methane is also a Greenhouse Gas (GHG) that contributes to global warming. According to Weyant et al. (1999) it has a 21 times higher impact on the earth's temperature than a Carbon Dioxide (CO_2) emission of the same mass. Thus LFG poses a serious threat and needs to be managed accordingly.

1.3 The landfill gas extraction process

Technical information contained in this section was supplied by Envitech solutions - a company specialising in Landfill Gas Extraction Project (LFGEP) development - unless stated otherwise.

The gas, mainly CH_4 and CO_2, is extracted by sinking a number of wells in the landfill. Vertical and horizontal gas wells are the two main types of wells currently in use.

Vertical gas wells have a sphere of influence with a radius of approximately 25m. Vertical gas well design and installation is shown schematically in Figure 1.3. Vertical wells are installed after a cell is filled up (referred to as an *inactive* cell). Half a meter diameter holes are drilled between three and fifty meters deep–depending on the depth of the landfill cell–to install the vertical wells. Horizontal gas collectors are installed 30m apart horizontally and 10m vertically in the landfill cell.

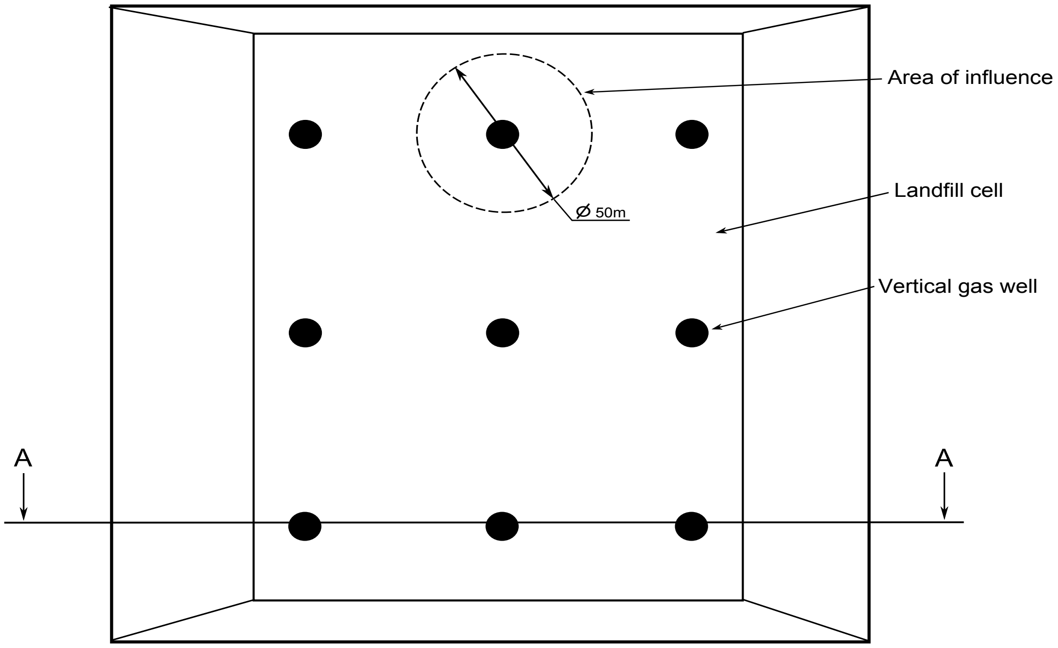
Horizontal wells are placed in a cell that is still receiving waste (referred to as an *active* cell). The horizontal gas collectors are placed in layers every ten meters as the cell is filled up as seen in Figure 1.4. The LFG extraction process is demonstrated in Figure 1.5. An extraction system is connected to the installed wells which creates a negative flow. The extracted LFG flows through a pipe system to the plant where it is used to generate electricity (Arigala et al., 1995). Electricity generators burn the compressed LFG and use the released energy for electricity production. (The landfill gas pump, flare station, gas engine, electricity generator, step - up transformer, switch gear and control room will be referred to as *the plant* throughout the rest of this paper. It takes $500m^3/h$ of LFG to power a 1MW electricity generator at full capacity. The electricity is sold to Eskom and the Certified Emission Reductions (CERs) produced are sold to a company in an industrialized nation that still exceeds their greenhouse gas emission quota (Michaelowa and Jotzo, 2005).

The creation of these wells is expensive and existing projects indicate that the individual flow rates of the various wells vary significantly . A preliminary study is crucial to verify the amount of methane in the landfill. The quantity and quality of CH_4 can be estimated by the amount of organic material decomposed in the landfill, the time since initial disposal, the annual rainfall, average temperature and the average atmospheric pressure (Young, 1989). This is especially a problem in South Africa as there are no accurate data available on the exact composition of landfills (Fourie and Morris, 2004).

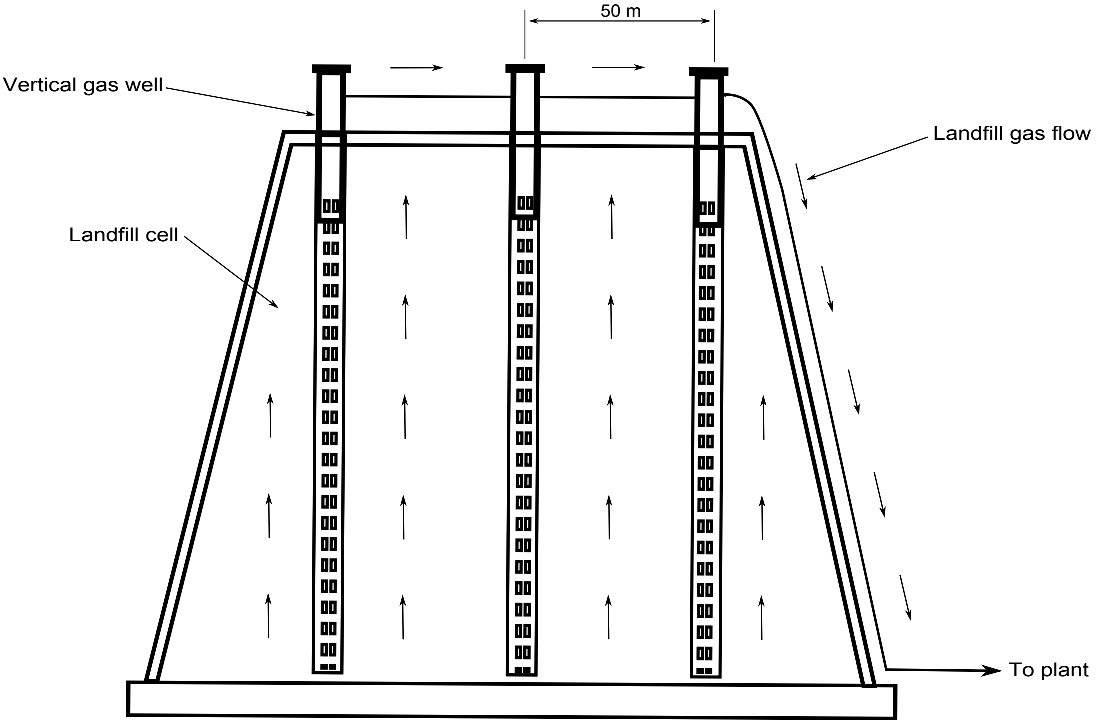
1.4 Carbon emission reduction trading

The process of LFG extraction has only become financially viable since the ratification of the Kyoto Protocol which implements the Clean Development Mechanism (CDM) (Michaelowa and Jotzo, 2005).

The Protocol is an agreement under which industrialized countries have to reduce their green house gas emissions by 5.2% compared to the year 1990 (Michaelowa and Jotzo, 2005). Countries and specific industries are set a target whereby their reductions are measured in equivalent tons of CO_2.The Clean Development Mechanism (CDM) allows for the creation of CERs which are created through emission reduction projects. Any environmentally friendly project where alternative energy sources are used or that prevents the release of GHGs qualifies as CER projects (Nordhaus et al., 1999). A methane reduction of one ton influences global warming twenty one times more (Weyant et al., 1999) than carbon dioxide of the same mass. The calculation of CERs for LFGEPs is summarised and simplified in Figure 1.6. The net CERs earned in the generators is calculated by taking the quantity of methane destroyed in the electricity process and deducting the



Top view



Section A-A: Side View

Figure 1.3: The area of influence and spacing of vertical gas wells

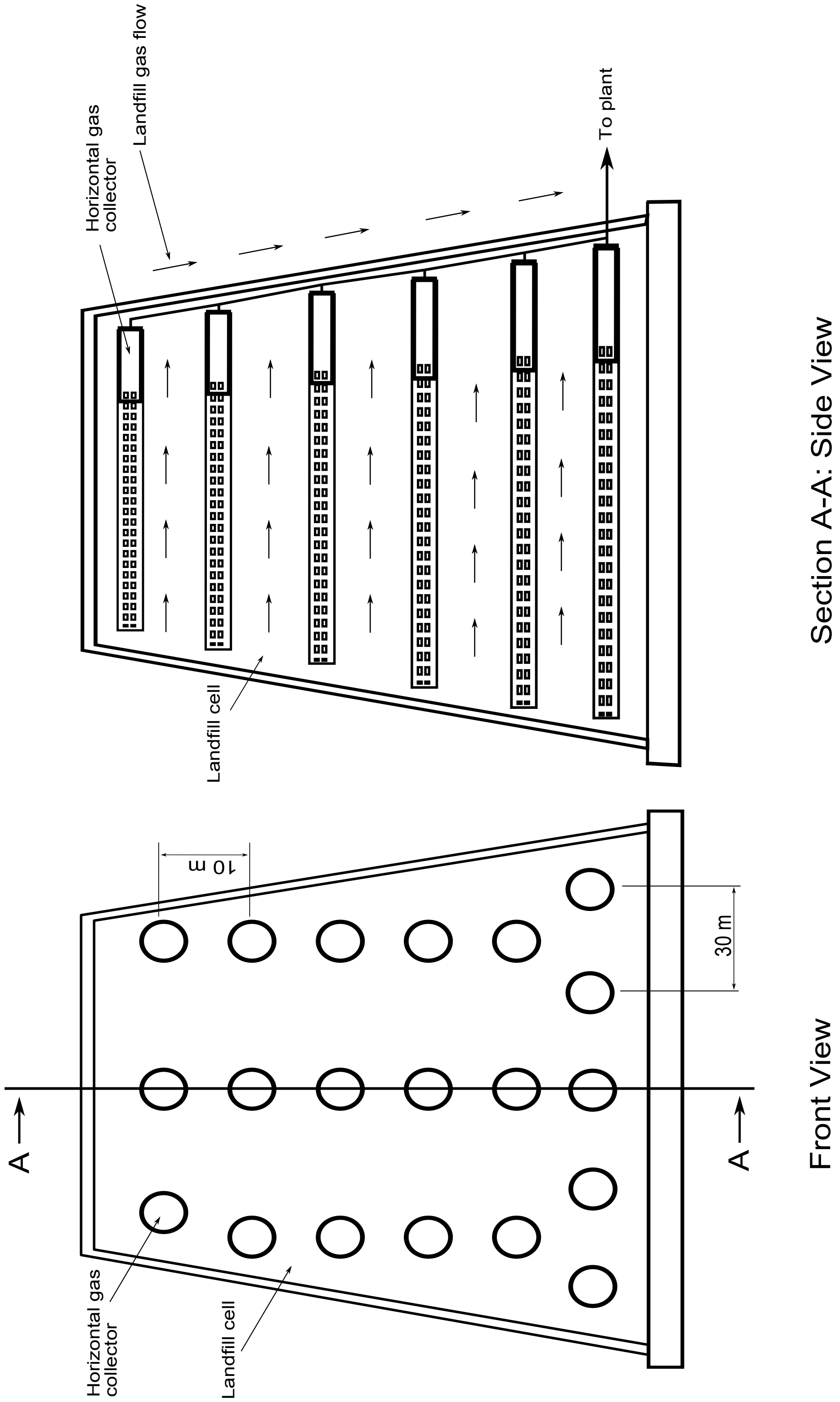


Figure 1.4: The area of influence and spacing of horizontal gas collectors

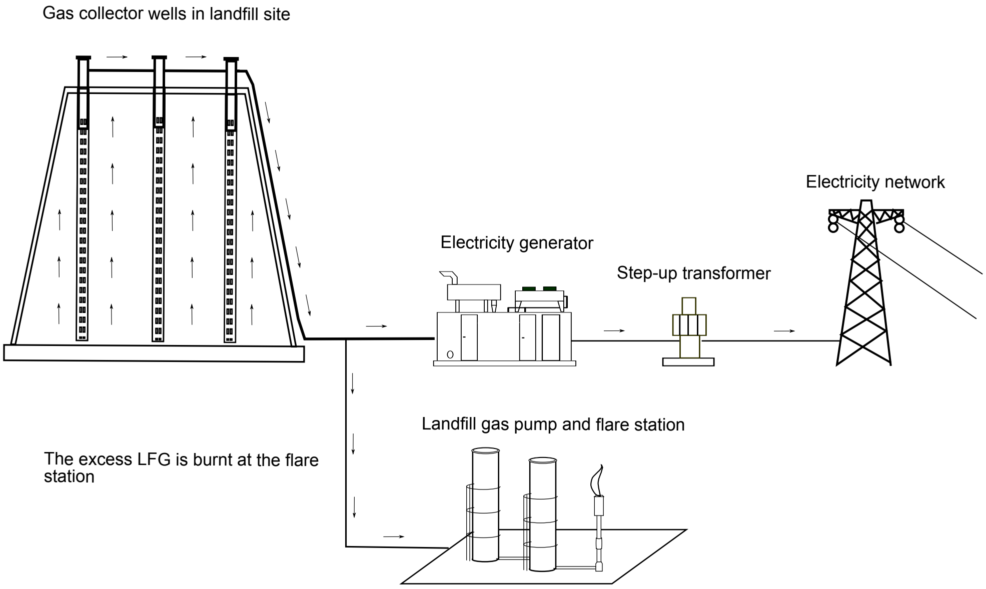


Figure 1.5: The flow of LFG from extraction to electricity generation

carbon dioxide emissions released while generating the electricity. Added to this is the methane destroyed in the flaring process minus the carbon dioxide emissions released when the methane was flared. The net quantity of emissions which in the absence of the project activity would have been produced in fossil fuel based power plants is added and the emissions from consumption of electricity in the project is deducted from the total to get the net CERs earned by the LFGEP. The interested reader is referred to Weyant (1993) for an overview of CERs trading and its role in reducing GHGs.

The ACM0001 methodology which gives complete and detailed information on CER calculations can be found on the United Nations Framework Convention on Climate Change (UNFCCC) web site (`http://www.unfccc.int`).

1.5 The Weltevreden LFG extraction project

The Weltevreden LFGEP project is managed by the Ekurhuleni Metropolitan Municipality and a number of contractors including *Envitech Solutions (Pty) Ltd.*, *Jones & Wagener Consulting Civil Engineers* and *Enviroserv (Pty) Ltd.* were contracted to develop and manage the site. Technical information on the Weltevreden project was provided by these companies unless stated otherwise. The Weltevreden LFGEP is used as a real-world case. Current methods and data logged at the

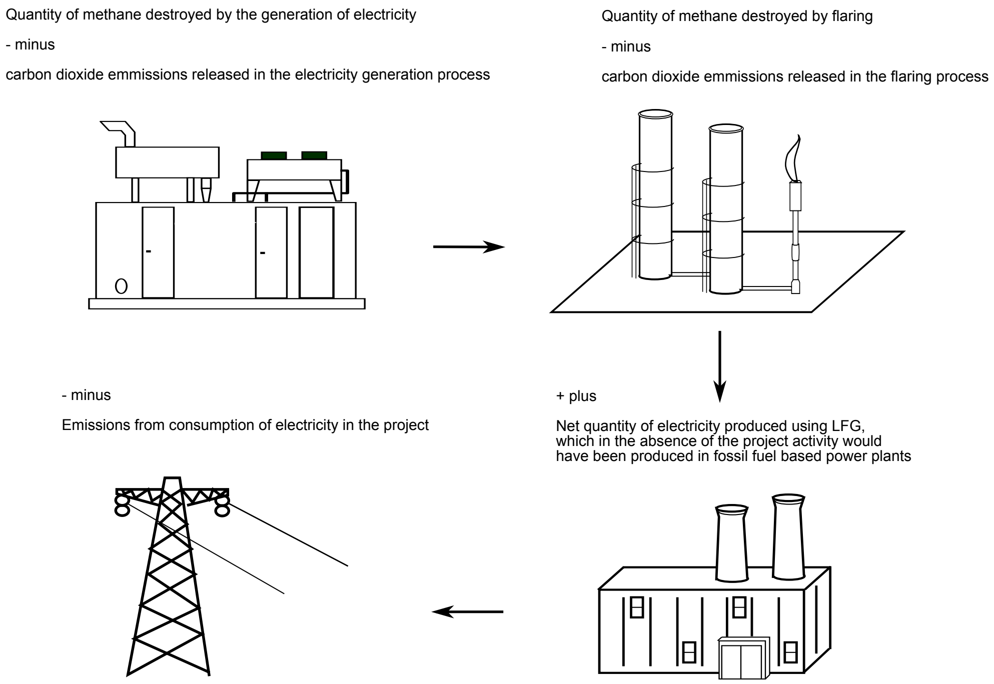


Figure 1.6: The calculation of CERs for a LFGEP

Weltevreden site is compared to the results of the researched techniques and outputs in this paper.

The Weltvreden landfill is situated in Northmead, Gauteng. It opened in 1995 and 200 000 tons of waste is deposited annually (Dollar, 2005). As seen in Figure 1.7 the Weltevreden landfill site currently (as on the 18th of May 2009) has 18 vertical wells in an older, closed cell (Cell 1) and 6 horizontal wells beneath a newer, active cell (Cell 4). The remainder of the cells is still undeveloped land and will be prepared to receive waste when older cells are filled up. The cells are excavated with side slopes of 1:2. A berm surrounds the cell and waste is deposited up to the surface or a few meters above with a side slope of 1:3.

Stevens (1984) describes a method for lining and capping the landfill to minimise leachate and LFG leakage into the surrounding environment: The bottom of the cells are prepared by first compacting the native soils. A compacted layer of clay is used as the base of the landfill. A plastic liner prevents leachate from leaking from the landfill and entering the environment. Perforated pipes surrounded by gravel collect leachate and channel it to the leachate management facility. A geotextile fabric is placed on top of the leachate collection pipe system to provide separation of solid particles from liquid which prevents clogging of the pipe system. Waste is deposited on top of a layer of sand or gravel that covers the geotextile fabric. The waste is covered with soil excavated at surrounding cells at the end of each working period. Compacted clay forms a cap over the waste when the cell reaches the permitted height. Another geomembrane prevents excess precipitation from entering the landfill and minimises the escape of LFG. A layer of sand, protective cover soil and finally top soil with vegetation is added to help rehabilitate the landfill.

The current capacity delivers 600 m^3 of LFG per hour . It is estimated that the Weltevreden landfill site will produce 4447 m^3/h of LFG by 2025 with an electricity potential of 15563 kW/h. The LFG flow rate will reach a maximum in the year 2025 after which it will rapidly decline. It will produce 5.77 million m^3 of LFG with an energy potential of 2884 Giga Watt hour (GWh) by the year 2034 (Blight, 2006).

There is a need for capacity expansion planning as LFG is currently only extracted from cell 1 and cell 4 and there is not an electricity generating facility as on the 18th of May 2009. Expansion planning has to be done for the remainder of the cells and a balance between the extracted LFG quantity and the plant has to be maintained to maximise the Return On Investment (ROI) of the project.

1.6 Problem definition

The project can be divided into two phases as outlined below.

Stage 1 The installation of horizontal or vertical gas wells in new areas of the landfill. Questions that have to answered in this stage are:

(a) When should a specific landfill cell be developed? This decision is based on the electricity generating capacity of the plant. The timing of cell development is crucial to ensure that as much of the extracted LFG can be used to generate electricity.

(b) Which type of gas wells (horizontal or vertical) will be the most profitable (i.e. extract the most LFG with the least cost) in a specific landfill cell? This is based on the shape and volume of the cell.

Stage 2 After *Stage 1* is completed successfully, additional generators should be added to the plant to accommodate any extra LFG that should be processed. Questions that have to be answered in this stage are:

(a) What should the generating capacity be to accommodate any LFG flow rate fluctuations?

(b) How many generators should be installed? (i.e. should one big generator be used because of economy of scale or will smaller gas turbines be more profitable).

A meeting with the managers of Envitech Solutions revealed that the capacity expansion plans are based on human intuition and that capacity expansion decisions for the expansion of the landfill and capacity expansion decisions for the plant are made separately.

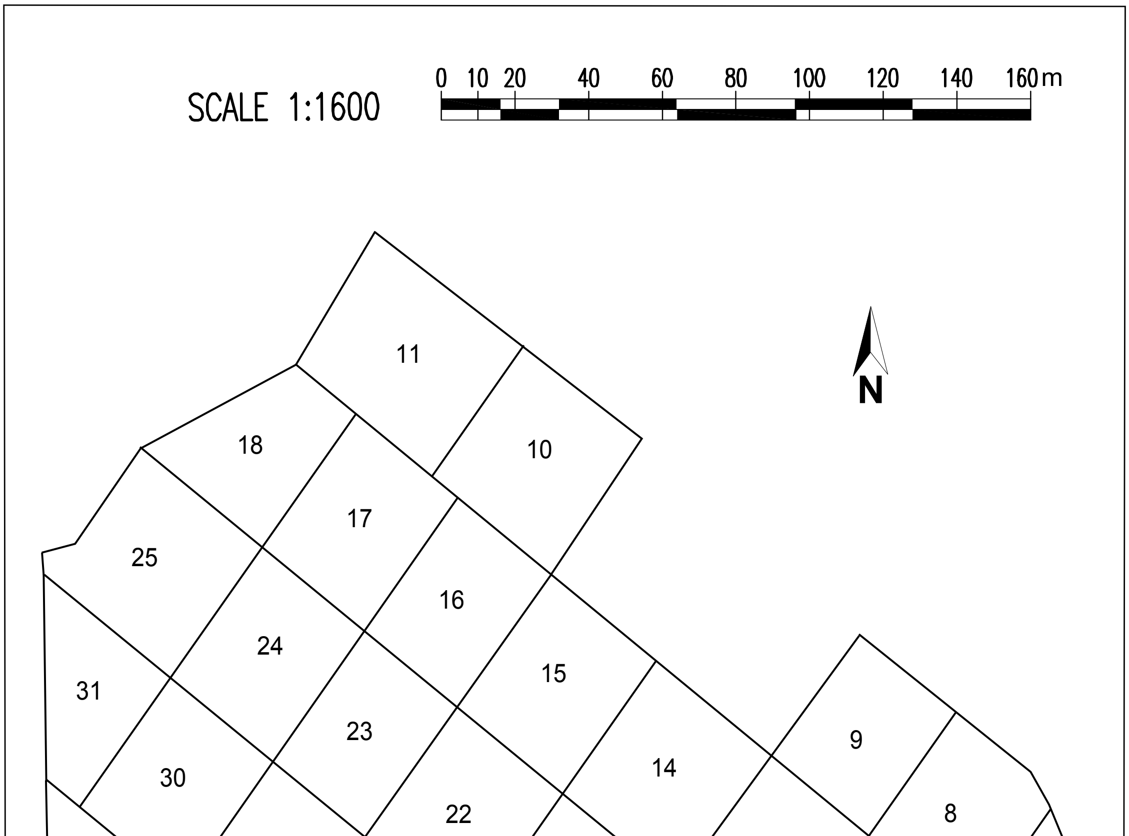


Figure 1.7: Layout of the Weltevreden landfill site

Used and adapted with the permission of Jones & Wagener Consulting Civil Engineers

The LFG production of the landfill site is not balanced with the electricity generating capacity of the plant. Any excess LFG that cannot be burnt in the generators is flared as illustrated in Figure 1.5. This means that LFG that could have been used to generate electricity and earn additional CERs is wasted. A normal cubic meter of LFG is worth up to nine times more if it is used to generate electricity rather than flared. Currently the two areas of the LFGEP are optimised individually and not balanced which leads to a decrease in ROI.

1.7 Research question

The objective of this study as outlined in Section 1.6 is to balance the LFG flow rate with the electricity generating capacity of the plant. The main research question is thus stated as follows:

> Given the historical and forecast LFG flow rate data, the layout and volume of each cell of the Weltevreden landfill site, will an integer programming approach and an adaptation of the news vendor problem approach give an improved ROI over the current capacity expansion plans of the Weltevreden LFGEP by balancing the extracted LFG quantity with the electricity generating capacity of the plant?

1.8 Research design and methodology

This paper covers improved capacity expansion methods and techniques specifically for the use by LFGEPs. The Weltevreden site will be used as a real-world case. The Capacity Expansion Models (CEMs) developed in this paper are compared to the current capacity expansion plans of *Jones & Wagener Consulting Civil Engineers* of the Weltevreden LFGEP.

The deliverables of the project are mathematical CEMs that maximise the ROI of LFGEPs. This is accomplished by balancing the two stages outlined in the *Problem definition* (Section 1.6) and illustrated in Figure 1.8. The quantity of LFG that the generators can handle should match the quantity of the extracted LFG to maximise the net income generated from the project. As stated in Section 1.3 a flow rate of at least $500m^3/h$ is needed to power a one mega watt generator at full capacity. Extracted LFG quantities exceeding the generators' capacity is flared which results in the loss of income from electricity and CER sales.

Quantitative inputs from historic and current data are used in the CEMs to find the capacity types that should be used and the periods in which the capacity expansion stages should take place. These stages will repeat throughout the lifetime of the project as Stage 2 will take outputs from Stage 1 as inputs and vice versa as illustrated in Figure 1.9. Gas wells are installed in a cell after which data are collected on the quantity and quality of the extracted LFG. The data are used to select the electricity generating capacity to accommodate the LFG. The efficiency of the electricity generation process is evaluated and used to plan for the next cycle of gas well installation. The two stages are optimised together by matching the LFG of the landfill to the generator capacity of the plant. This is an ongoing cycle as the generator capacity will be adapted for an increase in LFG production. These requirements have to be met in the course of the daily operations of the landfill site which will be discussed further in Section 3.2.

1.9 Document structure

Techniques used in the capacity expansion management of a wide variety of industries are discussed and evaluated in Chapter 2. Chapter 3 introduces the *cell development sequence* in Section 3.2 which gives a guideline for the effective capacity expansion of the landfill site. The *news vendor problem approach* is adapted and modified in Section 3.3 to give an indication of the number of generators needed at the plant. A comparison between the current and the modeled cell development sequence plan as well as an analysis of the results are discussed in Chapter 4. A conclusion on the study as well as any further developments are summarised in Chapter 5.

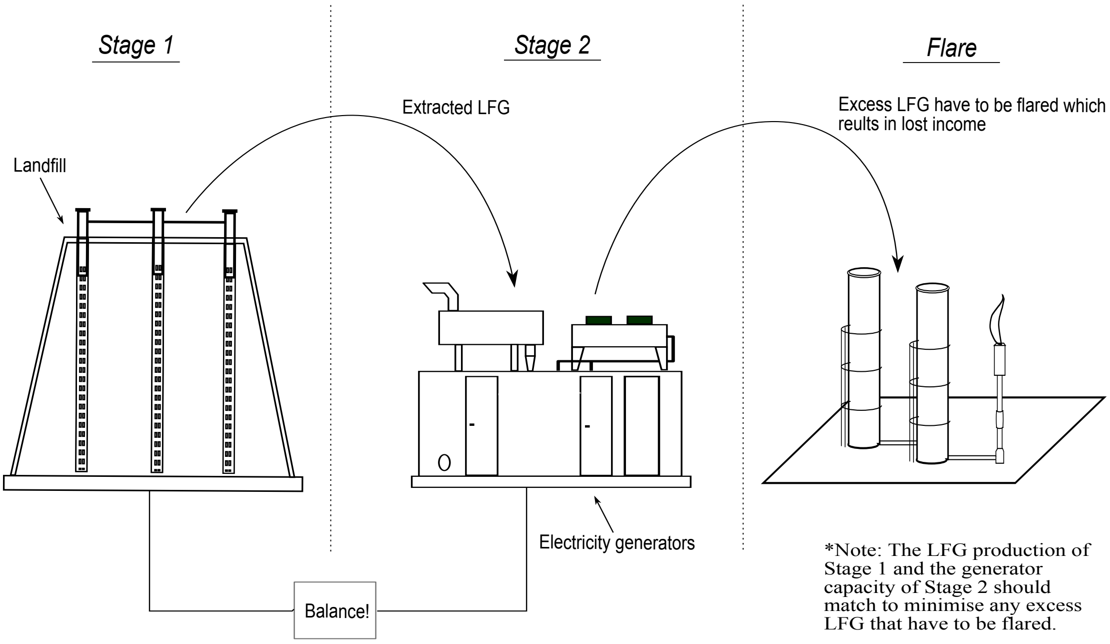


Figure 1.8: The importance of balancing Stage 1 and 2

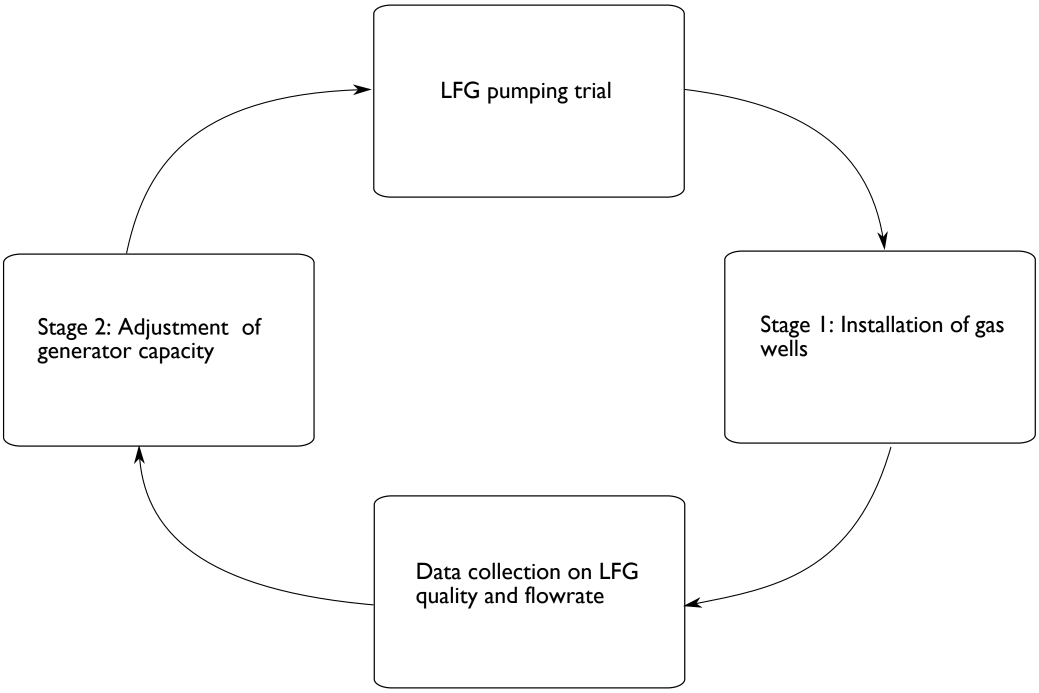


Figure 1.9: The continuous cycle of a LFGEP

Chapter 2

Literature review

Capacity planning in an expanding LFGEP can be approached by techniques used in the expansion planning of mining, electricity and oil industries as these sectors also have depletable resources (Baetz, 1990). Gunn (1998) concludes that the capacity determines the extraction rate and therefore the exhaustion of the reserve. The capacity size should thus be determined with production in mind and it is important to structure the solution around maximising profit over the lifetime of the project. Various capacity expansion techniques were researched and similar problems to the ones faced by the expansion of LFGEPs are included in the sections that follow.

The major decisions in capacity expansion problems are: expansion sizes, expansion times, expansion locations and/or capacity types (Freidenfelds, 1981). Capacity is added at discrete time intervals to meet increasing and variable demand as explained in Figure 2.1. As demand increases over time it exceeds current capacity. Additional capacity is added but because of economies of scale capacity is added that exceeds the current demand. Given the pattern of demand over time, the typical objective is to minimise the costs associated with the expansion process.

Planning for the expansion of capacity over a period of time is of vital importance in many applications within the private and public sectors. Effective capacity expansion planning can be used for short to mid term decisions in addition to being part of the business strategy that will give the company a competitive advantage. The use of capacity expansion models have been researched in environments as diverse as investment banking (Mieghem, 2003), the mining industry (Gunn, 1998), power and telecommunications (Freidenfelds, 1981), schools and hospitals (Ridge et al., 1998), the fast food and movie industry (Johnson, 2001). CEMs vary from the simple plant location problems that use LP relaxation to find the optimal solution (Bilde and Krarup, 1977) to more complex models of (Rajagopalan, 1992) that take the deterioration and obsolescence of the installed capacity into consideration. Various Operations Research methods have been proposed with dynamic programming (Erlenkotter, 1969), linear integer programming (Freidenfelds, 1981), stochastic integer modeling (Bean et al., 1992) and adapted Economic Order Quantity (EOQ)

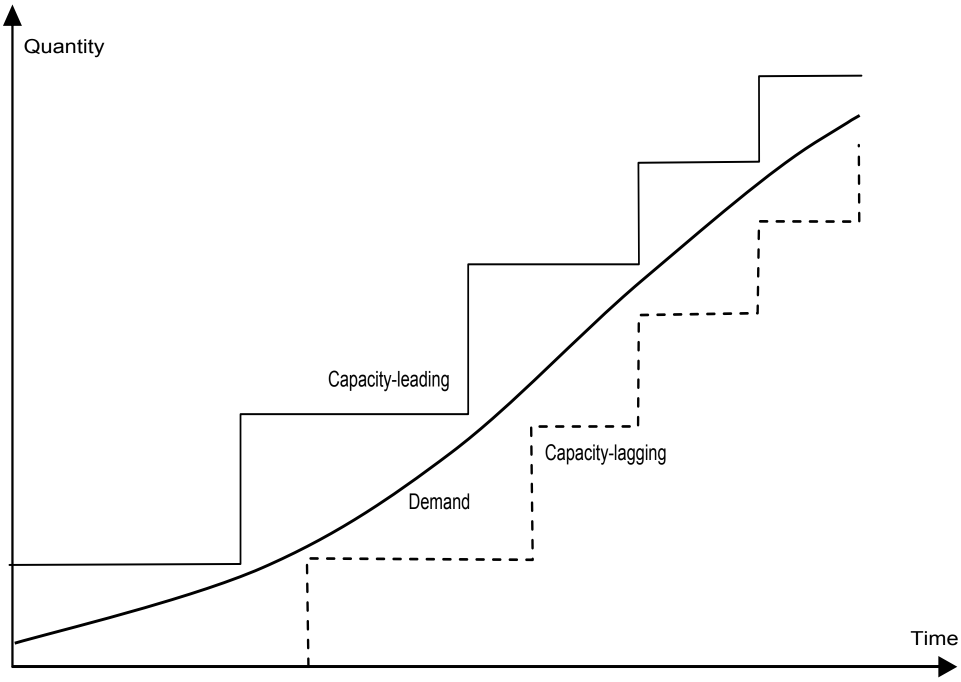


Figure 2.1: Demand vs. Capacity

(Freidenfelds, 1981)

models (Rajagopalan and Swaminathan, 2001).

The most suitable capacity expansion techniques are demonstrated in the sections that follow.

2.1 Dynamic programming techniques

Winston (2004) states that many Probabilistic Dynamic Programming (PDP) problems can be solved using recursions of the form

$$f_t(i) = max_a \left\{ \textit{(expected reward during stage } t|i,a) + \sum_j p(j|i,a,t) f_{t+1}(j) \right\} \tag{2.1}$$

where $f_t(i)$ is the maximum expected reward that can be earned during stages t, t+1,…end of the problem, given that the state at the beginning of stage t is i. The maximum in (2.1) is taken over all actions a that are feasible when the state at the beginning of stage t is i. In (2.1), $p(j|i,a,t)$ is the probability that the next period's state will be j, given that the current (stage t) state is i and action a is chosen.

Joubert (2008) formulates a Deterministic Dynamic Programming (DDP) recursion to solve the expansion problem of an electricity supplier over a period of 20 years by introducing the use of sets. The problem can be found in Winston (2004). The solution provides the optimal placement of power plants at a number of possible locations. It costs c_i to build a plant at site i and h_i to operate a plant at site i for a year. A plant at site i can supply k_i kilowatt hour (kWh) of generating capacity. During year t, d_t kWh of generating capacity is required. At most one plant can be built during a year. The recursion is formulated as: $f_t(s) \triangleq$ the minimum construction and operating cost for year t, t+1 ... T given that all units in set $\mathbf{S}$ has been built at the start of year t, where $\mathbf{S} \subseteq \mathbf{L} = \{1, 2 \ldots n\}$ and $c_0 = k_0 = h_0 = 0$.

for $t = T = 20$,

$$f_T(s) = min\left\{c_x + h_x + \sum_{y \in \mathbf{S}} h_y\right\} \tag{2.2}$$

where

$$x \in \{0, 1, 2 \ldots 5\}, x \notin \mathbf{S}$$

and

$$k_x + \sum_{p \in \mathbf{S}} k_p + \mathit{initial\ capcity} \geq d_t$$

for $t < T$

$$f_T(s) = min\Big\{c_x + h_x + \Sigma h_y + f_{t+1}(\mathbf{S} \cup \{x\} \diagdown \{0\})\Big\} \tag{2.3}$$

where

$$x \in \{0, 1, 2 \ldots 5\}, x \notin \mathbf{S}$$

and

$$k_x + \sum_{p \in \mathbf{S}} k_p + \mathit{initial\ capacity} \geq d_t$$

The solution is found by starting at $f_T(s)$ for $f \subseteq \mathbf{L}$, and working back to $f_1\{0\}$.

An example from Winston (2004) uses PDP to solve the expansion of an oil company's wells. The recursion yields

For t = T

$$f_T(d) = r_T q_T(d) \tag{2.4}$$

For $t < T$,

$$f_t(d) = max_a\Big\{r_t q_t(x) + f_{t+1}(d - x)\Big\} \tag{2.5}$$

where there are d dollars available to allocate for drilling at sites $1, 2, \ldots, T$, $0 \leq x \leq d$, x dollars are allocated to site t, the probability that oil will be found on site t is $q_t(x)$, if oil is found on site t it is worth r_t dollars.

In expansion problems involving two types of capacity Freidenfelds (1981) suggests the dynamic programming recursion

$$W(s_1, s_{12}) = min_{x_1, x_2}\Big\{C_1(x_1) + C_2(x_2)$$

$$+ W[s_1(x_1, x_2), s_{12}(x_1, x_2)]e^{-rt(x_1, x_2)}\Big\}$$

where

$W(s_1, s_{12})$ is the Net Present Value (NPV) of meeting all future demand optimally starting with spare levels of s_1 and s_{12}.
$x_1, x_2, C_1(x_1)$ and $C_2(x_2)$ are the sizes and costs of capacity expansions.
g_1 and g_2 is the demand growth.
$\tau(x_1, x_2)$ is the time of the next shortage starting with s_1 and s_{12} spare plus expansions of size x_1 and x_2:

$$\tau(x_1, x_2) \equiv min\left(\frac{s_1 + x_1}{g_1}, \frac{s_{12} + x_1 + x_2}{g_1 + g_2}\right)$$

$$s_1(x_1, x_2) \equiv s_1 + x_1 - g_1\tau(x_1, x_2), s_{12}(x_1, x_2) \equiv s_{12} + x_1 + x_2 - (g_1 + g_2)\tau(x_1, x_2).$$

The recursions in this chapter maximises profit or minimises cost over the lifetime of the expansion of the project. There is an initial fixed capital investment associated with the expansion of the current facilities. There is also an operating cost associated with each additional facility which is payable at the end of every stage of the project.

2.2 Integer programming formulations

(Freidenfelds, 1981) shows how capacity expansion problems can be cast in an integer programming formulation. Suppose only a finite number of capacity expansion sizes, $x_1, x_2, \ldots, x_n$, costing $C_1, C_2, \ldots, C_n$ which is only considered at a finite number of times, $t_1, t_2, \ldots, t_m$, where $D_1, D_2, \ldots, D_m$ capacity is required. Let y_{ij} be *integer* which is 1 only if capacity of size x_j should be added at time t. The objective function is given to minimise the NPV.

Minimise

$$\sum_{i=1}^{m}\sum_{j=1}^{n} C_j e_i^{-rt} y_{ij}$$

Subject to

$$\sum_{j=1}^{n}\sum_{k=1}^{i} x_j y_{kj} \geq D_i \quad \text{where } i = 1, \ldots, m.$$

The constraint will ensure that adequate capacity is available to meet the demand for each period. The objective function contains r which is the required rate of return. The inclusion of e_i^{-rt} thus ensures that the objective function is adjusted for the time value of money.

2.2.1 The branch-and-bound method

Many Integer Programming (IP) problems can be solved using the branch-and-bound method by implicitly enumerating all possible solutions. Branching on a chosen fractional-valued variable x_i

creates subproblems. If the subproblem is infeasible or it yields an optimal solution, it becomes unnecessary to branch further on this particular subproblem. It is said that the subproblem is *fathomed.* The technique is described by Winston (2003) as an elimination process where subproblems are created and then fathomed when it becomes futile to branch further on a particular subproblem.

Subproblems are created by branching on fractional-valued variables x_i. For example say that x_i assumes a fractional value between i and $i+1$ in a given subproblem (which will be referred to as the old subproblem). The generated subproblems are:

New subproblem 1 Old subproblem + constraint $x_i \leq i$.

New subproblem 2 Old subproblem + constraint $x_i \geq i+1$.

The following situations will cause a subproblem to be fathomed:

1. Infeasibility.
2. The solution to the subproblem is an optimal solution which is a *candidate solution* if it results in a better objective function value. Its objective function value becomes the current lower bound on the optimal objective function value of the IP.
3. The optimal objective function value for the subproblem does not improve the current lower bound and can thus be discarded.

Implicit enumeration may be used to find the optimal solution in IPs with binary variables.

Two new subproblems are created at a node for some free variable x_i by adding the constraints $x_i = 0$ and $x_i = 1$. It is not necessary to branch further if the best completion of a node is feasible. The node yields a new lower bound if the best completion is feasible and better than the current candidate solution. The node is eliminated if the best solution is not better than the current candidate solution. The node cannot yield a feasible solution or the optimal solution to the problem if there are one or more constraints that are not satisfied.

2.3 Probabilistic inventory models

Wagner and Whitin (1958) introduced the dynamic lot-size problem as an inventory or production problem but they also represent important Capacity Expansion Problems (CEPs). Rajagopalan and Swaminathan (2001) showed that EOQ models and CEMs are analogues.

2.3.1 News vendor problems

The same approach followed to solve problems called *news vendor problems* can be used to find the optimal capacity for an organization. News vendors must decide on the number of papers they wish to carry every day. If they carry too many papers they will be left with unwanted stock at the end of the day. There will be a loss of sales if a news vendor decides on carrying only a small number of papers and run out of stock before the day is over. The news vendor must find the the optimal number of papers to carry to balance the cost of under or over stocking. According to Winston (2004) problems where the following number of events occur are often referred to as news vendor problems .

1. An organisation must decide how many units (q) to order.
2. There is a demand of d units with a probability of $p(d)$. Assume that d is a nonnegative integer and let D be the random variable representing demand.
3. A cost $c(d, q)$ is incurred depending on d and q.

Let the cost function, $c(d, q)$, have the following form.

$$c(d, q) = c_0 q + (\textit{terms not involving } q) \qquad d \leq q \tag{2.6}$$

$$c(d, q) = -c_u q + (\textit{terms not involving } q) \qquad d \geq q + 1 \tag{2.7}$$

In (2.6) c_0 is the per-unit cost of being *overstocked.* c_u in (2.7) is the per-unit cost of being *understocked.* If ($d \leq q$) then the demand for the units is less than the quantity q that was ordered. If ($d \geq q + 1$) then the units were understocked. Let $E(q)$ be the expected cost for an order of q units and let it be a convex function as seen in Figure 2.2. The optimal order quantity q^* is the order of q units that minimises $E(q)$. From Figure 2.2 it is seen that q^* is the smallest value of q for which $E(q + 1) - E(q) \geq 0$. To calculate $E(q + 1) - E(q) \geq 0$ two possibilities are considered:

Case 1 ($d \leq q$). Ordering $q + 1$ instead of q units results in excess stock. This increases cost by c_0. The probability of this happening is $P(D \leq q)$.

Case 2 $d \geq q + 1$. Ordering $q + 1$ units instead of q means that the inventory is short by one less unit. This will decrease cost by c_u. The probability of Case 2 occurring is $P(D \geq q + 1)$ which equals $1 - P(D \leq q)$.

This means that ordering $q+1$ units will incur c_o more costs than ordering q units for a fraction $P(D \leq q)$ of the time. For the rest of the time, $1 - P(D \leq q)$, ordering $q + 1$ units instead of q will cost c_u less. Ordering $q + 1$ units will on average cost

$$c_o P(D \leq q) - c_u[1 - P(D \leq q)]$$

more than ordering q units. In summary

$$\begin{aligned} E(q + 1) - E(q) &= c_o P(D \leq q) - c_u[1 - P(D \leq q)] \\ &= (c_o + c_u)P(D \leq q) - c_u \end{aligned}$$

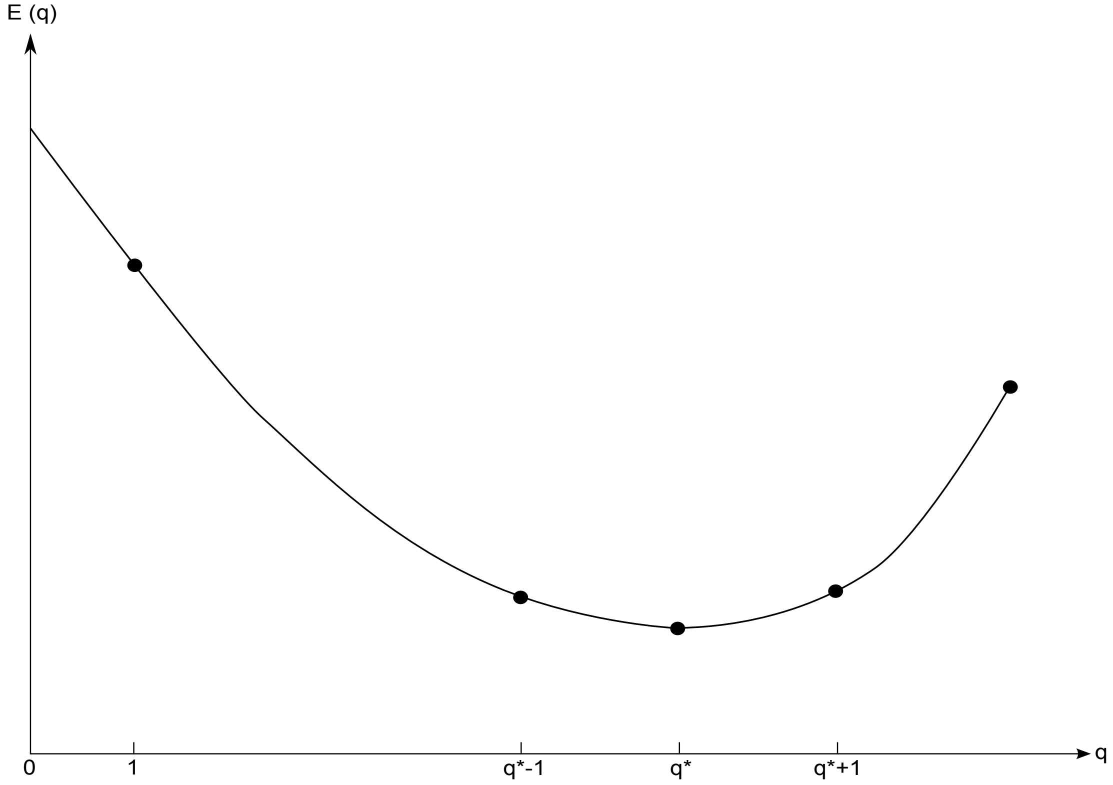


Figure 2.2: Determination of q by Marginal Analysis
(Winston, 2004)

E(q + 1) - E(q) will hold if

$$(c_o + c_u)P(D \leq q) - c_u \geq 0$$

or

$$P(D \leq q) \geq \frac{c_u}{c_o + c_u}$$

Let $(F(q) = P(D \leq q)$ be the demand distribution function. Since the use of marginal analysis is applicable, $E(q)$ will be minimised by the smallest value of q, (q^*), satisfying

$$F(q^*) \geq \frac{c_u}{c_o + c_u}$$

where $\frac{c_u}{c_o+c_u}$ is referred to as the *critical ratio*.

Angelus and Porteus (2002) makes the following comparisons between CEPs and *the news vendor problem*: c_u is the *understocking cost* for the current installed capacity that does not meet demand. Thus, there are parts that could have been made and sold with a profit if there was adequate capacity.

c_o is the *overstocking cost* of the capacity (e.g. down payments with interest on a loan, insurance costs, maintenance costs etc.) that has to be paid for the extra capacity.

Therefore, it is possible to find the critical ratio P_c and compute the optimal capacity size to maximise profit.

Khouja (1999) proposes extensions to the news vendor approach that include dealing with different objectives and utility functions, different supplier pricing policies, different news-vendor pricing policies and discounting structures, different states of information about demand, constrained multi-products, multiple-products with substitution, random yields, and multi-location models. These extensions are useful but were found to be unnecessary for the purpose of this study. A basic news vendor problem approach is used in Section 3.3 to find the optimal generator capacity for the plant.

Chapter 3

Method and formulation

Various techniques to aid in the capacity expansion of LFGEPs were identified in the literature review.

Stage 1 An integer programming approach proved to be the most suitable technique to establish which cell should be developed next as well as type of gas well that should be installed in this cell.

Stage 2 The *news vendor problem* approach proved to be the most suitable technique for calculating the optimal number of generators to install throughout the lifetime of the project. This technique can easily fit in with the integer programming approach used in Stage 1 because of its adaptability.

3.1 Source data

A survey of waste samples, mass of waste deposited, waste deposition rate, weighbridge data, and environmental factors such as temperature, humidity, atmospheric pressure are used in simulation software *GasSim* (`http://www.gassim.co.uk`) to simulate LFG production for an individual cell or landfill site. A first-order decay model that calculates the LFG generation for up to two hundred years is used to simulate the degradation of the waste. This output is used to calculate LFG emission of gases to the environment after allowing for LFG collection, flaring, utilisation (energy recovery), and biological methane oxidation. This is undertaken by using information on the site gas collection system, flare, generators and engineered barriers (cap and liner). It is assumed that LFG generated and not collected is in equilibrium and will be emitted from the landfill cap at a steady state, i.e. the model does not consider transient storage of LFG. Additionally the model calculates the concentrations of other major and trace gases emitted from flares and engines following combustion.

Data from the *GasSim* forecasts as well as historical data are used to develop and test the models developed in this paper. *Envitech Solutions (Pty) Ltd.* provided historical data that were logged at the Weltevreden landfill site. The extracted LFG flow rate (in m^3/h) as well as the LFG components and their concentrations are measured and recorded every fifteen minutes. The data were measured over a period of ten months for cell 1 and cell 4. Further information was obtained from the project design document which can be accessed via the UNFCCC website (`http://www.unfccc.int`), the draft capital budget (which was provided by the Ehurhuleni Metropolitan Municipality (EMM)) and the Department of Minerals and Energy (DME) website (`http://www.dme.gov.za`).

3.2 Stage 1: The cell development sequence

An integer programming approach is followed to solve the problems faced in *Stage 1* of the project. This method is chosen because a number of variables have to be solved simultaneously with the constraint of resources.

The project lifetime is 50 years and the Weltevreden landfill consists of 36 cells. The mathematical model described in Subsection 3.2.2 runs over a period of fifty years (2010 - 2060) and calculates the optimal cell development sequence for the remaining thirty four cells (vertical and horizontal wells are already installed in cell 1 and cell 4 respectively). Table 3.1 lists the various advantages and disadvantages of vertical and horizontal wells. Every cell has a unique area and depth which will determine what type of gas well will give the best ROI.

Table 3.1: Comparison between Vertical & Horizontal gas wells

	Vertical wells	Horizontal Wells
Capital cost (per hectare)	R1 million	R0.7 million
Operational costs (per hectare annually)	R2678	R3480
Active or inactive cell	Inactive	Active
Spacing	Radius of 25m	30m horizontally, 10m vertically

Vertical wells have an area of influence with a radius of 25m and are installed after a cell is filled to its capacity. Holes 1m in diameter are drilled after the cell has been covered up.

Horizontal wells are installed 30m apart horizontally and 10m vertically while the cell is still active i.e. the cell is still receiving waste.

The outputs of the model will be: a) in which year of the project should a cell be developed and b) what type of well (vertical or horizontal) should be installed in this well. These outputs will be based on the variables (e.g. area, depth, LFG production potential, capital cost and operational costs) associated with each cell. Electricity is currently sold for ninety four cents per kWh and CERs for a hundred and fifteen rand per CER. The income gained from electricity and CERs sales should therefore exceed the cost of developing a cell for it to be profitable.

A binary variable X_{ijk} will be equal to one if well type k should be installed in year j in cell i. This is stated in equation (3.1). Another binary variable Z_{ijk} will *trace* the wells where LFG is currently extracted from. This is accomplished by making Z_{ijk} equal to one for all the cells that are currently producing LFG. For instance, if $X_{4,7,2}$ is equal to one (this means that gas well type 2 - which is horizontal wells - should be installed in cell 4 in year 7). This will in turn cause $Z_{4,7,2}$, $Z_{4,8,2}$, $Z_{4,9,2}$,...,$Z_{4,50,2}$ to be equal to one. Operational costs and the minimum and maximum allowed flow rates can thus be traced by using the binary variable Z_{ijk}. The mathematical formulation for achieving this can be found below in equations (3.2), (3.6), (3.7) and (3.10).

The number of years that it will take to fill a particular landfill cell i to its maximum allowed limit is represented by the variable L_i. This is based on the forecast waste deposition rates as well as the cell's volume. A cell has to be filled to its capacity before a new cell is developed. This has been built into the model as this is an operational requirement.

Due to the limited funds allocated to the EMM there are constraints on the annual capital and operational expenditure. These amounts are represented using the variables C_j and P_j. The annual capital and operational expenditure is calculated for every year using the variables U_{ik} and Y_{ik}.

G_{1j} and G_{2j} place a constraint on the minimum and maximum allowed extracted LFG. This is done to ensure that the maximum quantity of extracted LFG is used to generate electricity and thus increase revenue.

3.2.1 Assumptions

There are a number of assumptions that have to be taken into consideration when the results are evaluated. The model was created with the current forecast data as well as the current layout of the landfill cells. It is assumed that current practice and design will remain the same throughout the life time of the project. These are stated as follow:

1. The shape and volume of the cells will not change during the life time of the project.

2. A cell will be filled to its capacity before developing a new cell as is current practice.

3. A leachate drainage network can easily and cheaply be installed to fit in with the cell development sequence plan.

4. Capital and operational expenditure for LFGEPs will increase relative to inflation.

5. The selling price of electricity and CERs will increase over and above inflation.

3.2.2 Mathematical formulation

$V_{ik} \triangleq$ The given income (in ZAR) from cell i if well type k is installed in cell i, where $i = \{1, ..., 34\}$ and $k = \{1, 2\}$.

$U_{ik} \triangleq$ The given capital expenditure (in ZAR) to install well type k in cell i, where $i = \{1, ..., 34\}$ and $k = \{1, 2\}$.

$Y_{ik} \triangleq$ The given annual cost (in ZAR) to operate and maintain cell i if well type k is installed in cell i, where $i = \{1, ..., 34\}$ and $k = \{1, 2\}$.

$L_i \triangleq$ The given time (in years) that it will take to fill up cell i to its maximum capacity with waste, where $i = \{1, ..., 34\}$.

$C_j \triangleq$ The given amount (in ZAR) that can be spent on additional gas wells in the whole landfill site in year j where $j = \{1, ..., 50\}$.

$P_j \triangleq$ The given amount (in ZAR) for operational costs in year j for the whole landfill site where $j = \{1, ..., 50\}$.

$G_{1j} \triangleq$ The minimum given flow rate (in standard m^3/h) that has to be maintained by the combined LFG production of all the landfill cells to meet the electricity generating capacity of the plant in year j where $j = \{1, ..., 50\}$.

$G_{2j} \triangleq$ The maximum given flow rate (in standard m^3/h) that should be maintained by the combined LFG production of all the landfill cells to meet the electricity generating capacity of the plant in year j where $j = \{1, ..., 50\}$.

$S_{iqk} \triangleq$ The given LFG quantity (in standard m^3/h) that will be produced in cell i in year q after well type k was installed in cell i where $i = \{1, ..., 34\}$, $k = \{1, 2\}$ and $q = \{1, ..., 20\}$.

$$X_{ijk} \triangleq \begin{cases} 1 & \text{if cell } i \text{ should be developed in year } j \text{ with well type } k, \\ & \text{where } i = \{1, ..., 34\}, j = \{1, ..., 50\} \text{ and } k = \{1, 2\} \\ 0 & \text{otherwise} \end{cases} \tag{3.1}$$

$$Z_{iqk} \triangleq \begin{cases} 1 & \text{if } X_{ijk} = 1 \text{ where } q \geq j \text{ for all } i = \{1, ..., 34\},\ j,\ q = \{1, ..., 50\},\ k = \{1, 2\} \\ 0 & \text{otherwise} \end{cases} \tag{3.2}$$

Maximise

$$\sum_{i=1}^{36} \sum_{j=1}^{50} \sum_{k=1}^{2} \left(V_{ik} X_{ijk} - U_{ik} X_{ijk} + Y_{ik} Z_{ijk} \right) \tag{3.3}$$

Subject to

$$\sum_{j=1}^{50}\sum_{k=1}^{2} X_{ijk} \leq 1 \qquad \forall \quad i = \{1, ..., 36\} \tag{3.4}$$

$$X_{ijk} + X_{wqr} \leq 1 \qquad \forall \quad i = \{1, ..., 36\},\ j = \{1, ..., 50\},\ k = \{1, 2\},\ w \neq i, r \neq k, j \leq q < j + L_i \tag{3.5}$$

$$X_{i1k} \leq Z_{i1k} \qquad \forall \quad i = \{1, ..., 36\}, k = \{1, 2\} \tag{3.6}$$

$$Z_{i,j+1,k} \geq X_{i,j+1,k} + Z_{ijk} \qquad \forall \quad i = \{1, ..., 36\}, j = \{1, ..., 50\},\ k = \{1, 2\}, 1 < j < 50 \tag{3.7}$$

$$\sum_{i=1}^{36}\sum_{k=1}^{2} X_{ijk}U_{ik} \leq C_j \qquad \forall \quad j = \{1, ..., 50\} \tag{3.8}$$

$$\sum_{i=1}^{36}\sum_{k=1}^{2} Z_{ijk}Y_{ik} \leq P_j \qquad \forall \quad j = \{1, ..., 50\} \tag{3.9}$$

$$\sum_{i=1}^{36}\sum_{k=1}^{2} G_{1j} \leq S_{iqk}Z_{ijk} \leq G_{2j} \qquad \forall \quad j = \{1, ..., 50\},\ q = \{1, ..., 20\} \tag{3.10}$$

Equation (3.3) maximises the ROI for the remainder of the undeveloped cells over the fifty year lifespan of the project. Constraint (3.4) ensures that each cell can only be developed once with one type of gas well. Constraint (3.5) stops the model from choosing a new cell to be developed before the current cell has reached its capacity. This is achieved by using the variable L_i which gives the time in years for cell i to reach its capacity with the current deposition rates. The conditions $w \neq i$ and $r \neq k$ are included because this is already stated in constraint (3.4) and does not need to be repeated. Constraint (3.6) and (3.7) forces Z_{iqk} to be one if $X_{ijk} = 1$ for all $q \geq j$. Constraint(3.8) and constraint(3.9) ensure that the annual capital and operational budgets are not exceeded. The maximum and minimum allowed flow rates accepted by the model are included with constraint (3.10).

The model is solved using Lingo™ optimisation software which uses the branch-and-bound method for this particular solution. This method is described in detail in Subsection 2.2.1. The computational time required to reach the optimal solution to the problem is currently eight minutes.

3.3 Stage 2: The news vendor problem approach

The feasibility of adding additional electricity generating capacity after every expansion phase is verified using the *news vendor* approach. This technique is discussed in detail in Subsection 2.3.1. The added capacity can be in the form of generators (in various mega watt capacities) or smaller gas turbines. This approach makes use of the *Concept of Marginal Analysis.* It will calculate the trade-off between the cost of acquiring and operating electricity generating capacity versus the additional income that will be generated from the trade in CERs and electricity sales.

3.3.1 The news vendor approach adapted for the Weltevreden LFGEP

Data of the flow rate (in m^3/h) were taken from 03/08/2008 to 31/03/2009. A data logger automatically records the flow rate, pressure, temperature and components of the extracted LFG every 15 minutes. A summary of the data is given in Table 3.2.

Table 3.2: Summarised flow rate data of the Weltevreden landfill

μ	σ	C_u	C_o	$\frac{C_u}{C_o+C_u}$	Capacity
$612m^3/h$	$24m^3/h$	$R2.13c$	$R0.14c$	0.9383	$638m^3/h$

The mean (μ) of the current flow rate and the standard deviation (σ) is only representative for the current LFG extraction from cell 1 and cell 4. This will change as waste is deposited and new cells are developed. The critical ratio will also change as electricity prices and the demand for CERs increase and the price of generators increase relative to inflation. It is thus critical to use the most recent data available for the model to be accurate. The mean, standard deviation and the critical ratio are used as inputs to the normal distribution to calculate the optimal electricity generating capacity. This will in turn be used as an input for the cell development sequence planning model.

Chapter 4

Execution and analysis of results

4.1 The cell development sequence

The differences between the current and modeled cell development sequence plan is summarised in Table 4.1. Horizontal wells are represented with an *H* and vertical wells with a *V*. The current plan makes use of vertical wells for cell 1 and horizontal wells for the remainder of the landfill cells. This causes the extracted LFG to exceed the electricity generating capacity over extended periods of time. The repercussions are that the excess LFG is flared which results in decreases in revenue from CERs and electricity sales.

Table 4.1: Comparison of the current and modeled sequence

	Current sequence		Modeled sequence	
Year	Cell no.	Well type	Cell no.	Well type
2010	1	H	25	H
2011	2	H	30	V
2012	2	H	2	H
2013	3	H	2	H
2014	3	H	26	V
2015	5	H	18	H
2016	5	H	7	H
2017	6	H	24	V
2018	6	H	3	H
2019	7	H	3	H
2020	8	H	9	H
2021	8	H	34	V
2022	9	H	35	V

2023	10	H	6	V
2024	10	H	6	V
2025	11	H	26	H
2026	12	H	15	H
2027	12	H	31	V
2028	13	H	8	V
2029	13	H	8	V
2030	14	H	16	V
2031	15	H	16	V
2032	16	H	20	H
2033	16	H	20	H
2034	17	H	14	V
2035	18	H	27	V
2036	19	H	33	V
2037	19	H	5	H
2038	20	H	5	H
2039	20	H	10	V
2040	21	H	10	V
2041	21	H	19	H
2042	22	H	19	H
2043	23	H	12	H
2044	24	H	12	H
2045	25	H	17	V
2046	26	H	21	H
2047	27	H	21	H
2048	28	H	28	H
2049	29	H	29	H
2050	30	H	36	H
2051	31	H	36	H
2052	32	H	22	V
2053	33	H	32	H
2054	34	H	11	H
2055	35	H	13	H
2056	36	H	13	H
2057	36	H	23	V

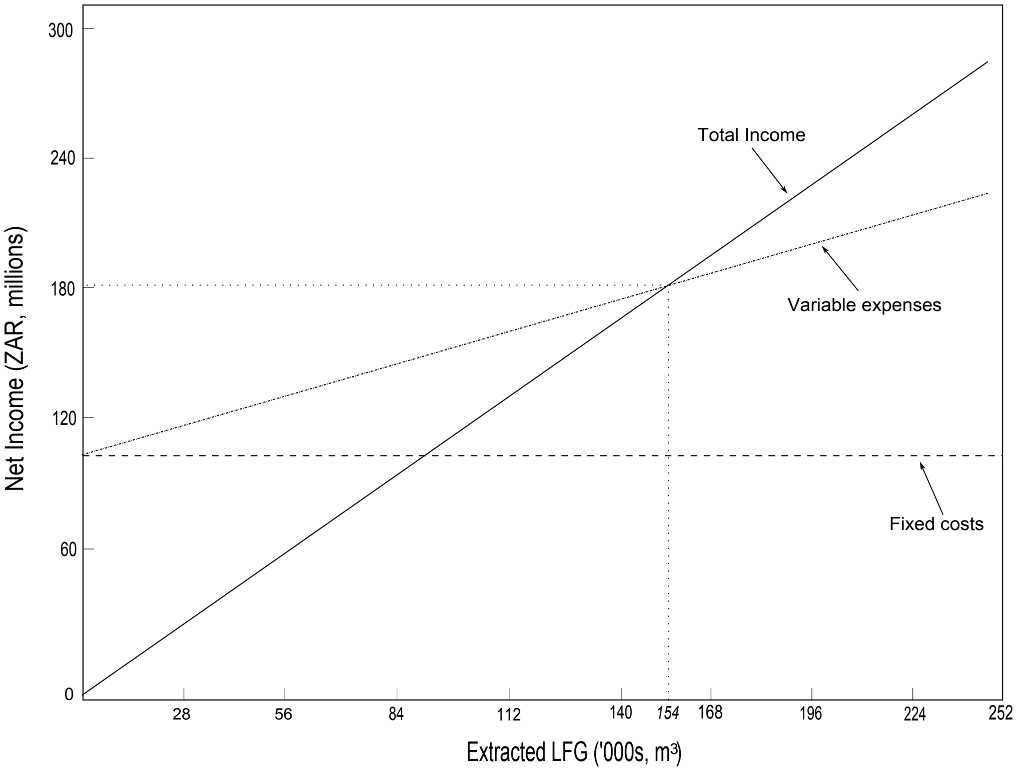


Figure 4.1: Break-even analysis

The Weltevreden LFGEP should process (extract and use to generate electricity) at least one hundred and fifty four standard cubic meters of LFG to cover its capital investment. The break-even analysis is graphically illustrated in Figure 4.1. The operations and maintenance costs are represented with *variable expenses* in the figure. The variable expenses increase with an increase in the quantity of extracted LFG. This is due to additional scheduled and unscheduled maintenance that has to performed on the generators as well as on the LFG extraction network.

4.2 The news vendor problem approach

The critical ratio corresponds to a probability in the normal distribution. The mean μ, standard deviation σ and critical ratio can thus be used to find the optimal electricity generating capacity for the plant. The function *norminv* can be used to solve the problem in a spreadsheet. For this specific solution the inputs are entered as: *=norminv(0.938,612,24)*. The result is that the generator capacity should currently be enough to process $638m^3/h$ of LFG. A 1MW generator needs $500m^3/h$ of LFG to run at full capacity as stated earlier in Section 1.3. Electricity generating capacity of 1.276 mega watt will thus currently be optimal for the plant. Smaller generators or gas turbines have been found to be suitable for smaller loads. An analysis for the costs and benefits associated with gas turbines should be made for small additions to current capacity. The addition of a small 0.3 mega watt gas turbine is profitable in this case as the income generated from it will exceed its cost. The optimal generator capacity can easily be updated by using the news vendor problem approach as the landfill expands and the LFG quantity increases.

4.2.1 Sensitivity analysis

The variables that have the most effect on the objective function have been identified in Figure 4.2. A realistic increase in the two revenue streams of the project were projected. Emmanuel (2008) forecasts that South Africa's electricity price will increase dramatically over the next few years while Rio (2007) foresees the same for the price of CERs. An electricity price increase will have the most advantageous effect on the projects net income as this forms over eighty percent of the project's revenue. This will make LFGEPs an even more attractive investment.

The capital investment associated with gas well and generator installation is the major contributor to the total costs of the project. The increase in the prices of vertical and horizontal wells as well as generators and the impact this will have on the net income forms part of the sensitivity analysis. An increase in the capital costs of vertical wells will see an increase in the number of cells the model select to install horizontal wells in and vice versa.

It is especially the capital costs of generators that is a main contributing factor on the objective function of the model. Hopefully the costs of containerized generators will decrease as LFGEPs become more widespread. An increase in the sales price of electricity and a decrease in generator costs will cause the *critical ratio* used in the news vendor problem to be closer to *one*. This means that it will be more profitable to have excess generator capacity rather than lose money from electricity sales.

The O&M costs have an impact on the net income of the project as seen in Figure 4.1. However it is not near as big as the influence of the capital expenditure on the project's ROI. The O&M costs increase linearly with an increase in the extracted LFG quantity which means that its impact on the net income will always be predictable.

4.3 Comparison between the current and modeled CEMs

The EMM supplied the financial data in this section unless stated otherwise.

The outcomes of the different scenarios of the current and modeled cell development sequence plan are illustrated in Figure 4.3 and Figure 4.4 and further discussed below.

The current cell development sequence plan Horizontal wells are to be installed in all the remaining cells. This means that LFG is extracted from the beginning of waste deposition in the cell. While this method could have been advantageous if the refunding for plant expansion had been available, it is not currently the case as there is limited electricity generating

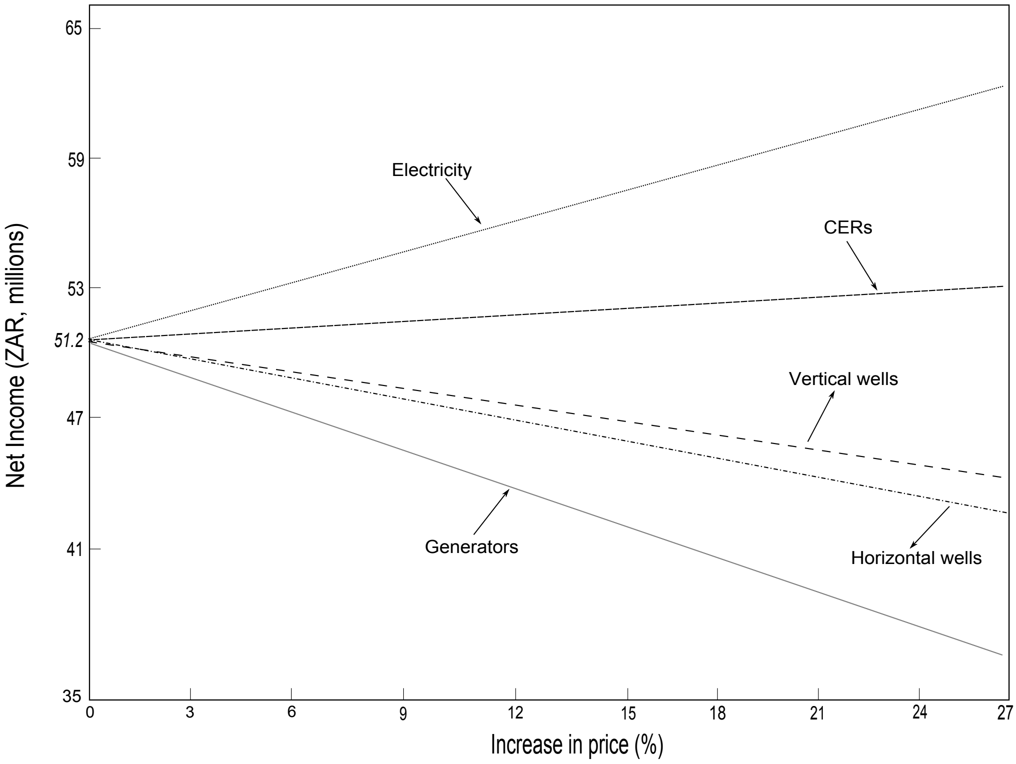


Figure 4.2: The impact of the main contributing variables on the objective function

capacity throughout the life time of the Weltevreden LFGEP. The limited capacity causes large quantities of extracted LFG to be flared instead of being used to generate electricity. This in turn lowers revenue from the trade in CERs and electricity sales.

The modeled cell development sequence plan The model's output *balances* the extraction of LFG with the electricity generating capacity of the plant. This is achieved by setting a minimum and maximum flow rate that has to be maintained throughout the life time of the project. The mathematical formulation is given in Section 3.2, equation (3.10). The minimum required flow rate covers the cost of the project with no profit i.e. at the break even point. The maximum allowed flow rate uses all the electricity generating capacity of the plant while allowing a small quantity to be flared. Flaring of a portion of the LFG is inevitable as waste is continually being deposited and the LFG building up in the landfill cells have to be extracted. The minimum and maximum allowed flow rates are continuously adjusted as additional generators or gas turbines are added to the plant. The trade-off between the cost and income from the added electricity generating capacity is calculated using the adapted *news vendor* problem as explained in Section 3.3.

A financial summary of the Weltevreden LFGEP is given in Table 4.2. The NPV method was used because according to W. Seal (2009) the internal rate of return method assumes that

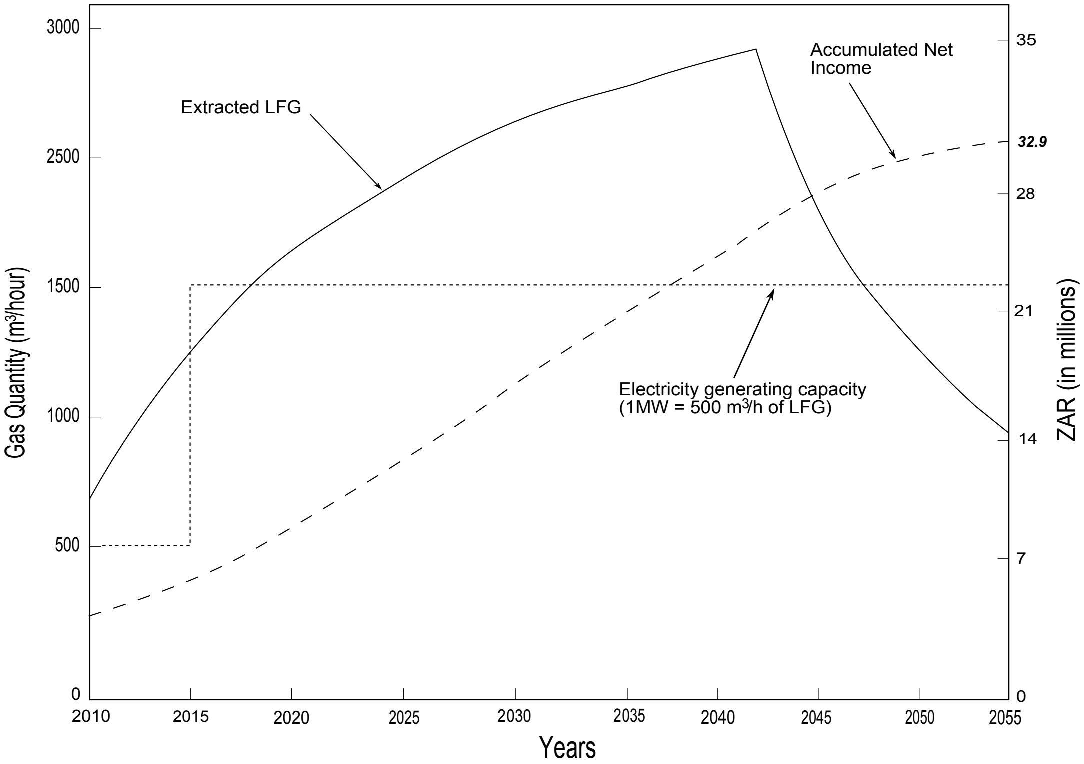


Figure 4.3: The current cell development sequence plan

cash flows generated during the life time of the project is immediately reinvested elsewhere with the internal rate of return of the project. This is unrealistic especially if the internal rate of return is very high. Furthermore, a profitability index is used to compare the current and modeled cell development sequences. This is necessary as the income and costs associated with the two alternatives are different. The profitability index is defined as the *present value of cash in flows* divided by the *investment required*.

The profitability index of the modeled plan is more desirable than the current one as seen in Table 4.2. The ROI of 22% is very attractive compared to other investments as illustrated in Figure 4.5. A further breakdown of the income and costs are given in Tables 4.3 and 4.4. The modeled capacity expansion plan has higher operational and capital costs associated with it but also promises much higher gains.

The various investment opportunities summarised in Figure 4.5 illuminates the attractive ROI that LFGEPs offer. Data from the South African Reserve Bank's web site (`http:///www.reservebank.co.za`) and from the quarterly bulletin published by the Reserve Bank were used to calculate the ROI for the various investments. Negotiable certificates of deposits (NCD) and the Johannesburg Stock Exchange (JSE) all share index are the strongest contenders with returns of 13.5% and 10.3% respectively. South African Benchmark overnight rate on deposits (Sabor) and

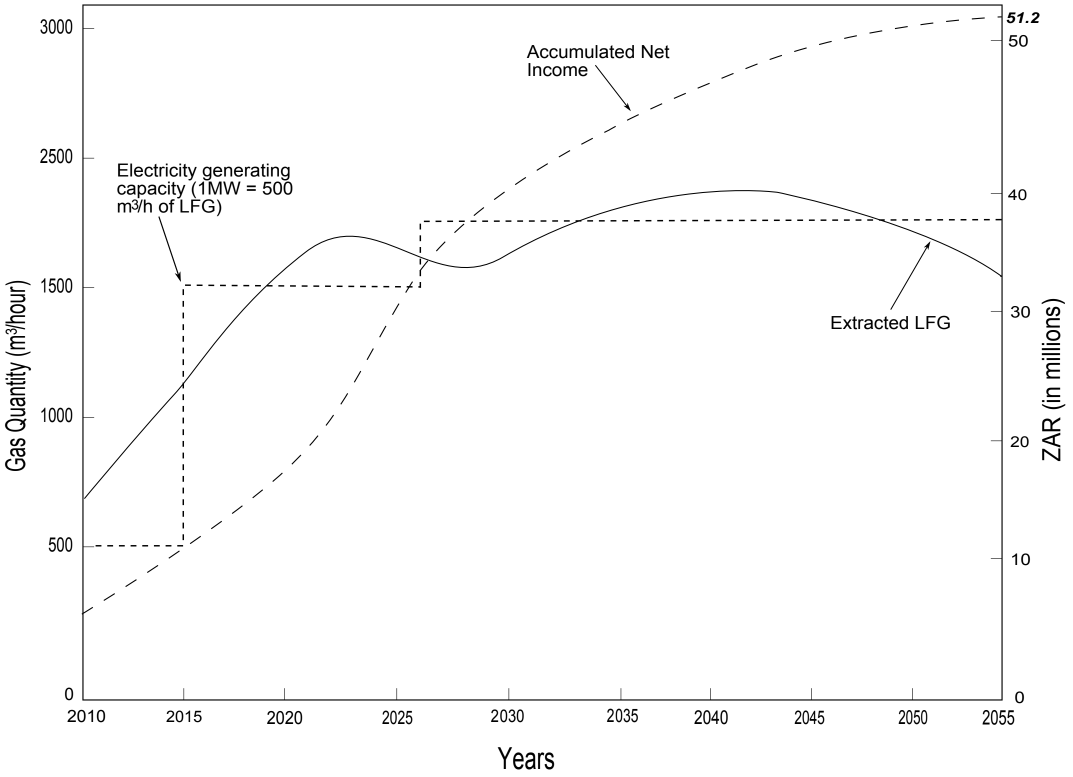


Figure 4.4: The modeled cell development sequence plan

JSE dividends are safe investments but will not be considered if higher returns are required.

The high return for the Weltevreden LFGEP does come with a fair amount of risk. There is no guarantee that the LFG yield will be as high as the forecast suggests. The level of uncertainty associated with LFG production will decrease as LFGEPs become more widespread and further research is done in this field.

The Weltevreden LFGEP is financed through the capital budget of the EMM and does not use money provided by the World Bank as is the case with many CDM projects. Net income generated from the project is used to cover the general expenses of the EMM (e.g. municipal staff salaries, waste removal vehicles' fuel, water and electricity bills etc.).

The Weltevreden LFGEP is a self-sustaining project which benefits the whole community. The ongoing mutual relationship between the project and the community is illustrated in Figure 4.6.

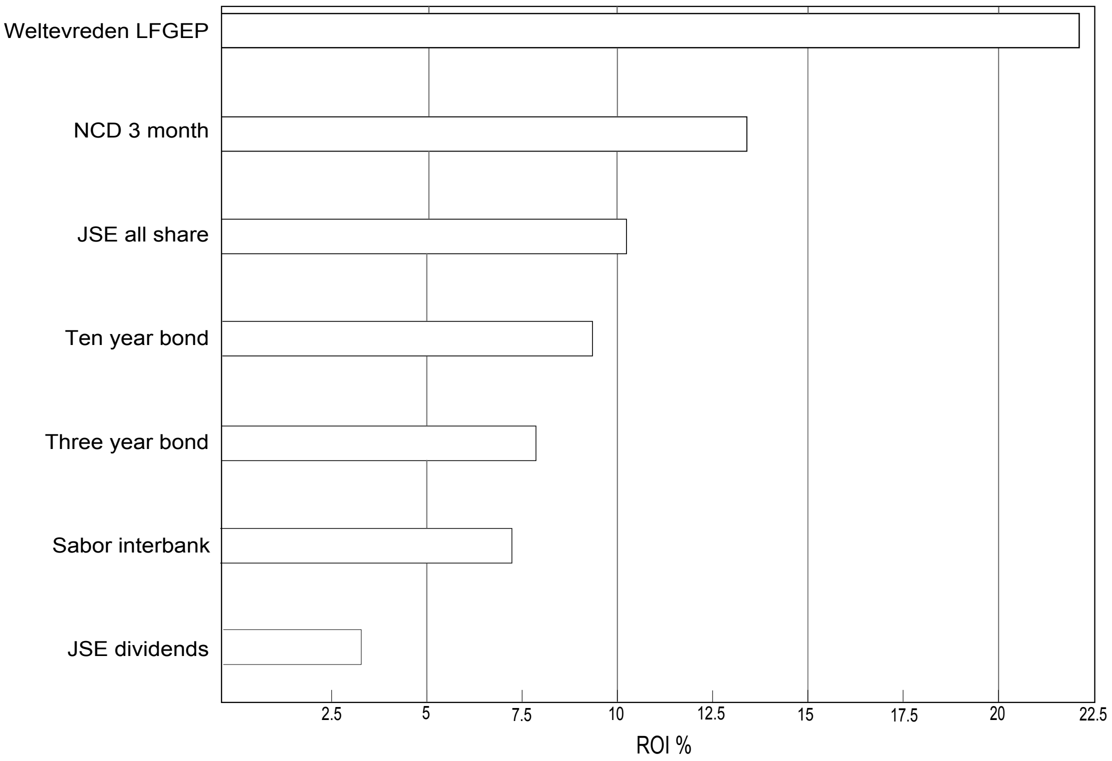


Figure 4.5: Comparative rates of return on different benchmark investments

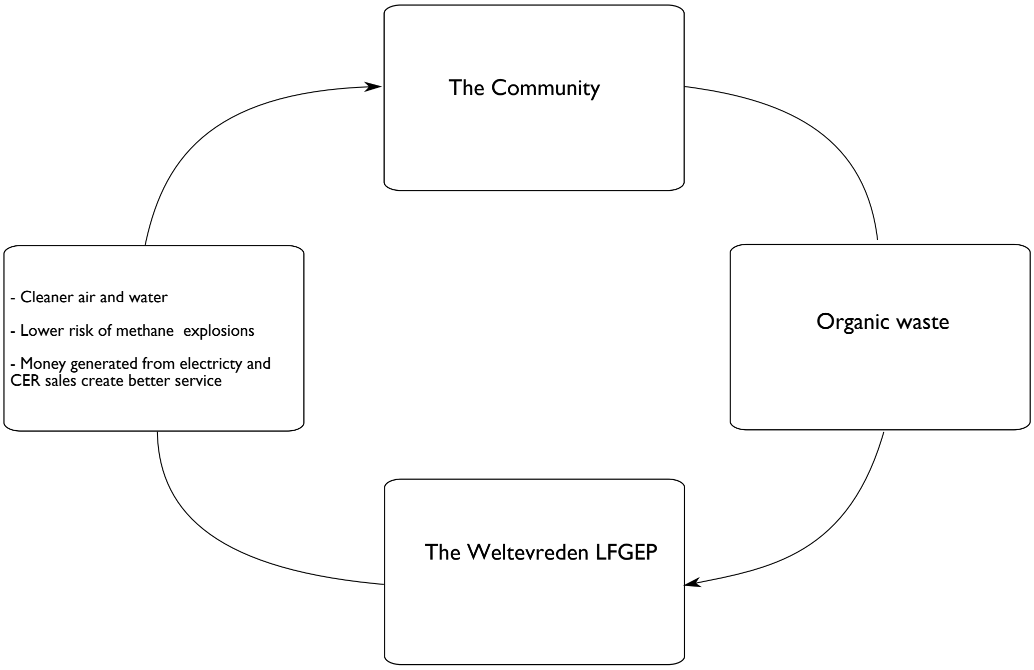


Figure 4.6: The mutual relationship shared by the Weltevreden LFGEP and the community

Table 4.2: Summary of the economic analysis for the Weltevreden LFGEP (in ZAR)

	Cell development sequence plan	
	Current	Modeled
Project revenue	215,556,543	279,617,554
Project costs	182,675,565	228,375,320
Net income	32,880,978	51,242,234
ROI	18%	22%
NPV:		
10%	3,747,685	5,299,927
15%	2,515,407	3,577,848
18%	2,084,088	2,984,341
Profitability index	1.18	1.22

Table 4.3: Breakdown of the income for the Weltevreden LFGEP (in ZAR)

	Cell development sequence plan	
	Current	Modeled
Revenue generated from:		
The trade in CERs	150,889,580	195,732,287
Electricity sales	64,666,962	83,885,266
	215,556,542	279,617,553

Table 4.4: Breakdown of the expenditure for the Weltevreden LFGEP (in ZAR)

	Cell development sequence plan	
	Current	Modeled
Capital investment		
Landfill	91,250,000	108,375,000
Plant	2,925,000	3,900,000
O&M costs (50 years)		
Landfill	3,000,000	2,000,000
Plant	85,500,000	114,000,000
	182,675,565	228,375,320

Chapter 5

Conclusion and future research

This paper identified the lack of research in CEMs for LFGEPs. The absence of Industrial Engineering techniques used in this area is mainly due to the novelty of LFGEPs. The Operations Research literature as well as literature in other fields were reviewed on relevant CEMs and ways to modify and adapt the models to the capacity expansion of LFGEPs. An integer programming approach and an adaptation of the news vendor problem deemed to be the most appropriate techniques for the required CEM.

The researched techniques were tested at the Weltevreden LFGEP and the results compared to the current capacity expansion plans of Envitech Solutions. The modeled capacity expansion plan showed an increase in ROI of 4% compared to the current plan. The reason for this is the ability of the two models to balance the extracted LFG with the electricity generating capacity of the plant. This results in a higher quantity of LFG used in the electricity generating process. This in turn leads to an increase in revenue from the trade in CERs and electricity sales.

Research into the optimisation of CEMs for landfill gas extraction projects is still very limited and leaves ample opportunities for improvement. More powerful and realistic mathematical models can be developed using heuristic techniques such as simulated annealing, genetic algorithms or the tabu search algorithm. The models researched in this paper will hopefully form the base of such future research. However, the results of these models are still promising and it will be possible to use the techniques developed in this paper to optimise current LFG extraction projects (Marianhill and La Mercy landfills in Durban, KwaZulu-Natal) as well as future projects in South Africa and the rest of the world. LFGEPs will, according to Hettiaratchi (2007) and Strachan (2003), spread rapidly in developing countries such as India, China and the rest of Africa in the following ten years.

Bibliography

A. Angelus and E. L. Porteus. Simultaneous capacity and production management of short-life-cycle, produce-to-stock goods under stochastic demand. *Management Science*, pages 399–413, 2002.

S. G. Arigala, T. T. Tsotsis, I. A. Webster, Y. C. Yortsos, and J. J. Kattapuram. Gas generation, transport, and extraction in landfills. *Journal of environmental engineering*, 121(1):33–44, 1995.

B. W. Baetz. Capacity planning for waste management systems. *Civil Engineering and Environmental Systems*, 7(4):229–235, 1990.

J. C. Bean, J. L. Higle, and R. L. Smith. Capacity expansion under stochastic demands. *Operations Research*, pages 210–216, 1992.

Sherri Berger and John Mann. Landfill gas primer - an overview for environmental health professionals, 2001.

O. Bilde and J. Krarup. Sharp lower bounds and efficient algorithms for the simple plant location problem. In *Studies in Integer Programming: Proceedings of the Institute of Operations Research Workshop, Sponsored by IBM, University of Bonn, Germany, Sept. 8-12, 1975*, volume 1, pages 79–97. North Holland, 1977.

G. E. Blight. Graded landfill requirements in South Africa - the climatic water balance classification. *Waste Management & Research*, 24(5):482, 2006.

L. H. Dollar. Moisture retention of municipal solid waste mixed with sewage sludge and ash in a semi-arid climate. *Waste Management & Research*, 23(3):209, 2005.

Z. Emmanuel. The demand for residential electricity in South Africa. *Energy Policy*, 36(9), 2008.

D. Erlenkotter. *Preinvestment planning for capacity expansion: A multi-location dynamic model.* Stanford University, 1969.

A. B. Fourie and J. W. F. Morris. Measured gas emissions from four landfills in South Africa and some implications for landfill design and methane recovery in semi-arid climates. *Waste management & research*, 22(6):440, 2004.

J. Freidenfelds. *Capacity expansion: analysis of simple models with applications.* North Holland, 1981.

Eldon Gunn. A brief review of operations research in mining. *The Bulletin*, 1998.

D. M. Johnson. Lessons learned from industry: applying capacity planning in an institution for higher education. *Managerial Finance*, 27(5):17–32, 2001.

Dr. J.W. Joubert. Operations research: Boz 321 class notes, 2008.

M. Khouja. The single-period (news-vendor) problem. *Omega*, 27(5):537–553, 1999.

P. Kjeldsen and E. V. Fischer. Landfill gas Migration–Field investigations at skellingsted landfill, denmark. *Waste management & research*, 13(5):467, 1995.

Tobias Koch. Landfill gas extraction and utilisation in China potential technology, 2001.

A. Michaelowa and F. Jotzo. Transaction costs, institutional rigidities and the size of the clean development mechanism. *Energy policy*, 33(4):511–523, 2005.

J. A. Van Mieghem. Commissioned paper: capacity management, investment, and hedging: review and recent developments. *Manufacturing & Service Operations Management*, 5(4):269–302, 2003.

W. D. Nordhaus, J. G. Boyer, Yale University, and Cowles Foundation for Research in Economics. Requiem for Kyoto: an economic analysis of the Kyoto Protocol. *Energy Journal - Cambridge*, 20:93–130, 1999.

S. Rajagopalan. Deterministic capacity expansion under deterioration. *Management science*, pages 525–539, 1992.

S. Rajagopalan and J. M. Swaminathan. A coordinated production planning model with capacity expansion and inventory management. *Management Science*, pages 1562–1580, 2001.

J. C. Ridge, S. K. Jones, M. S. Nielsen, and A. K. Shahani. Capacity planning for intensive care units. *European journal of operational research*, 105(2):346–355, 1998.

P. Del Rio. Encouraging the implementation of small renewable electricity cdm projects. *Renewable and Sustainable Energy*, 11(7):1361–1387, 2007.

C. Stevens. Landfill lining and capping. *U.K.A.E.A.*, (no. 37996):pp. 61, 1984.

H. M. Wagner and T. M. Whitin. Dynamic version of the economic lot size problem. *Management Science*, 5(1):8996, 1958.

J. P. Weyant. Costs of reducing global carbon emissions. *The Journal of Economic Perspectives*, pages 27–46, 1993.

J. P. Weyant, J. Hill, A. S. Manne, and R. Richels. The costs of the kyoto protocol. *The Energy Journal (Special Issue)*, 1999.

W. B. Whitman, T. L. Bowen, and D. R. Boone. The methanogenic bacteria. *The prokaryotes*, 1: 719767, 1992.

G. M. Williams and N. Aitkenhead. Lessons from loscoe; the uncontrolled migration of landfill gas. *Quarterly Journal of Engineering Geology and Hydrogeology*, 24(2):191–207, 1991.

Wayne L. Winston. *Introduction to Mathematical Programming*, volume One. Brooks/Cole, fourth edition edition, 2003.

Wayne L. Winston. *Introduction to Probability Models*, volume Two. Brooks/Cole, fourth edition edition, 2004.

A. Young. Mathematical modelling of landfill degradation. *Journal of Chemical Technology & Biotechnology*, 46(3), 1989.