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University of KwaZulu-Natal Work Order 3 (Contract # 22834)

Economic Evaluation of Faecal Sludge Disposal Routes

Phase 5 Report

Pollution Research Group - University of KwaZulu-Natal

Final Report

Economic Model (Spreadsheet)

Appendices

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Project Summary Information

Contract Information

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Executive Summary

The **La**trine Bio-solids **De**hydration and **Pa**steurisation (LaDePa) process is a treatment system for faecal sludge, reducing the volume of solids to be disposed of and producing a pathogen-free product that may be used in agricultural applications. The objective of this study was to carry out an economic evaluation of (i) the LaDePa process and (ii) a total combustion processes for sludge disposal and/or re-use. These were compared against the option of disposing of sludge to landfill. A versatile economic model was developed that enables a total cost comparison of the processes to be carried out, from the latrine pit to the point of end disposal or sale of the treated sludge product.

The model was developed and populated by making use of data from eThekwini Water and Sanitation (Durban, South Africa) on the pit emptying process and the operation of the LaDePa pelletising machine. Additional data on the pit sludge, LaDePa pellet and combustion ash characteristics were obtained through laboratory analysis and from existing data within the Pollution Research Group (University of KwaZulu-Natal). A data set was also obtained for faecal sludge collection, transport and treatment in Dakar, Senegal and used for validation.

The model can accept inputs for various emptying processes and combinations of sludge conveyance options. It accounts for sludge storage and pre-treatment requirements prior to the LaDePa and combustion processes. Operational inputs have been disaggregated to enable application of the model in a range of contexts.

The potential value of sludge endproducts was calculated by two methods: (i) value based on the NPK content of the sludge endproducts compared to commercially available fertilisers and (ii) partial budget analysis of the economic benefit of replacing commercial fertilisers with sludge endproducts for a specific crop.

Normalised sensitivity indices, SI_N, were calculated for selected input parameters to provide a comparative measure of the relative impact the different inputs had on the calculated costs of sludge disposal. For the eThekwini case, costs of faecal sludge disposal calculated by the model for all three disposal routes were found to be most sensitive to changes in the length of the pit-emptying cycle (SI_N > 0.7 for all options) and the sludge accumulation rate (SI_N>0.5 for all options) in the pit. In addition, the costs of treatment and disposal via the LaDePa process were found to be particularly sensitive to the sludge dry solids content (SI_N 0.42) and the volumetric capacity of the LaDePa plant (SI_N 0.48). The cost of disposal via combustion was found to have a high sensitivity to a greater number of factors, including the number of pits emptied per cycle (SI_N 0.48), the wet sludge density (SI_N 0.47), the sludge dry solids content (SI_N 0.56) and the capital cost of the plant (SI_N 0.42).

At the base case eThekwini conditions, the costs for all three disposal options were similar (376 USD/pit for disposal via the LaDePa process, 359 USD/pit for combustion and 326 USD/pit for landfill. All costs included emptying and conveyance costs), with the LaDePa option being slightly more expensive than the other two. The cost of producing LaDePa pellets was calculated to be 1 226 USD/tonne. In comparison, the maximum competitive selling price for the pellets, if they were to be used to fertilise a dry beans crop in place of an existing organic fertiliser, was 18 USD/tonne. It should be noted that this value is based on the NPK nutrient content of a very small number of pellet samples, and did not take into account micro-nutrients. On this basis however, the sale of pellets will not cover the cost of producing them.

However, the LaDePa option may still be preferable to combustion[1] or landfill. The model does not monetise all the associated benefits with disposal via the LaDePa process, for example, return of a greater proportion of carbon and nutrients to the land, reduced carbon emissions, environmental benefits of reducing disposal to landfill and more appropriate job creation. In addition, the model indicates that if

[1] It should be noted that the combustion process modelled did not incorporate any energy recovery or electricity generation, but was purely used as a sludge disposal route with the only possible benefit being recovered from the ash product.

operating conditions are optimised, the LaDePa process can be more cost-effective than combustion and landfill. The following parameters were indicated as significant:

- Optimal level of decentralisation of LaDePa plants;
- Structure of the pit-emptying programme: longer pit-emptying cycles are preferable, and the frequency of pit-emptying should be optimised;
- Control of sludge accumulation rates (and to an extent the wet sludge density) through improved solid waste collection and appropriate design for new pit latrines;
- Control of sludge dry solids through improved drainage and appropriate pit designs;
- The number of households included in a pit-emptying programme;
- The cost of pre-drying sludge;
- The minimum feed dry solids that can be accepted by the LaDePa cf. the minimum that can be accepted by combustion;
- The cost of the LaDePa lease;
- The cost of landfill.

Where landfill is treated as an avoided cost, the non-monetised benefits are taken into account, and operating conditions optimised, it is shown that the LaDePa process can be the most cost-effective option.

This work also highlighted the co-dependency between operating conditions (for example, frequency of emptying, sludge accumulation rate, sludge detritus content and sludge dry solids content), which the model does not fully take into account, and the additional complexity implied by this. Further work is needed to refine the model to take into account these relationships.

The final version of the Spreadsheet Model is attached as a separate file.

Acknowledgements

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1 Introduction

1.1 Background

The majority of the urban population in Africa, Asia and Latin America use on-site sanitation systems for the management of human excreta (Strauss et al., cited in Montangero & Strauss 2002; Ingallinella et al 2002). These systems include basic unimproved pit latrines, ventilated improved pit latrines, bucket latrines, septic tanks and composting toilets. Conventional waterborne sewerage is not a viable prospect in the short to medium-term for the majority of people who currently use on-site sanitation systems, for reasons of cost, access and sustainability (water and energy demands and nutrient losses) (Rosenquist 2005, Muller 2005). The appropriate management of on-site sanitation systems will therefore be a critical challenge for years to come.

Untreated faecal sludge is a health and environmental hazard due to a high load of pathogens, organic material, nitrogen, phosphorus and potentially heavy metals. Failure of sludge management systems can result in human and environmental exposure to faecal sludge via the following routes:

- The overflow of latrine pits and septic tanks (Klingel et al 2002);
- Disposal of untreated sludge into drains, watercourses or onto land (Montangero & Strauss 2002; Ingallinella et al 2002; Cofie et al 2006);
- Unsafe use of sludge in agriculture, risking pathogen exposure to workers and consumers of the agricultural products (Klingel et al 2002).

This study specifically considers the management of ventilated improved pit latrines (VIPs) where faecal sludge is accumulating at a rate higher than it is degrading, and therefore has to be removed at intervals from the facility. When the sludge cannot be re-buried on site close to the existing latrine (for example, due to lack of space or a high water table), it must be transported off-site for treatment and disposal.

The aims of the 'ideal' treatment/disposal system for faecal sludge are to:

(i) Prevent the exposure of the human population to pathogens and the degradation of the environment through eutrophication;
(ii) Recover useful components from the sludge, including nutrients and energy;
(iii) Minimise the economic costs associated with the above and ideally produce a financially self-sustaining system through the sale of recovered product(s) from the sludge.

The city of Durban, South Africa, has pioneered the development of a dehydration-pasteurisation process (LaDePa – **La**trine Bio-solids **De**hydration and **Pa**steurisation) which converts pit latrine waste into pasteurised pellets with a high carbon and nutrient content. This study looks at the financial viability of that process and compares it with both a total combustion process and disposal of sludge to hazardous landfill.

1.2 Project objective

This project considers three possible routes for the processing of VIP sludge:

(i) A dehydration-pasteurisation process producing pellets suitable for agricultural land application;
(ii) A total combustion process producing ash, for land application or final disposal;
(iii) Disposal to hazardous landfill.

The LaDePa dehydration-pasteurisation process has been trialled by the eThekwini municipality in KwaZulu-Natal, South Africa. A 6 m3/day throughput plant has been constructed to process the sludge removed from 35 000 pit latrine facilities across the municipality. The total cost of processing sludge through this plant, and the economic viability of its replication and scale-up in other locations, is not yet clearly understood.

The objective of this work was therefore to carry out an economic evaluation of the LaDePa and total combustion processes for sludge disposal and/or re-use and compare them against the 'do nothing' option of landfill. This was done through the development of a versatile Microsoft Excel spread sheet based economic model that enables a total cost comparison of the processes to be carried out, from the latrine pit to the point of end disposal or sale of the treated sludge product. The model is intended for decision-makers to meaningfully evaluate the two routes for the management of pit latrine sludge, taking into account different local conditions, e.g. the distances between pits, frequency and cost of pit-emptying, the nature of the sludge removed, transport and processing costs and the local market value of the end product.

The model was calibrated with data from the eThekwini Water and Sanitation (EWS) context (South Africa) but the input parameters are sufficiently generalised to allow the model to be populated with data from other contexts. As an example, data were obtained from West Africa (Dakar, Senegal) in order to identify the suitability of the LaDePa process to treat the sludge generated from other on-site sanitation systems. The majority of the systems used in Dakar are septic tanks resulting in a much "wetter" sludge than that from pit latrines which could impact on the process.

1.3 Project deliverables

The project was divided into a number of deliverables. These are listed in Table 1.1 together with the date on which the report was submitted. Each deliverable report provided an overview of the model development at that stage and focussed on a specific aspect of the model. The latest version of the spread sheet model at that stage was also provided.

Table 1.1: Summary of Deliverables

Deliverable	Date submitted	Main focus	Appendix No.
Phase 1	28th March 2013	Overview of methodology	1
Phase 2	6th May 2013	Model development using EWS data	2
Phase 3	3rd June 2013	Agricultural aspects Agricultural spreadsheet	3a 3b
Phase 3b	8th July 2013	Interim progress report	4
Phase 4	12th August 2013	Phase 4 report Final report from Dakar Spread sheet Appendix to report	5a 5b 5c 5d

Each of these reports is attached as Appendices to this final report.

This final deliverable report therefore provides the following information:

- Background to each of the disposal routes being modelled;
- A summary of the process followed in the development of the model;
- An overview of how to use the model;
- A summary of that data input sets for the model from eThekwini municipality, South Africa, and Dakar, Senegal;
- A description of the model validation process and sensitivity analysis, and key results from these;
- Details of the endproduct valuation methods used and key results, including assessment of the agricultural value of the endproducts;
- An overview of the relationships between model inputs and outputs, and impact these have on the economic viability of the LaDePa process and combustion;
- A preliminary assessment of the economics of the LaDePa process for eThekwini municipality;
- Suggestions for further development of the model and future work.

The final spread sheet model is attached together with an explanation of how to enter and interpret the data. Instructions for using the model are provided in the spread sheet model rather than a separate manual, with an overview provided in Section 4 of this report.

2 Modelling faecal sludge management (FSM)

2.1 The faecal sludge management chain

The basic faecal sludge management (FSM) 'chain' is summarised in Figure 2.1.

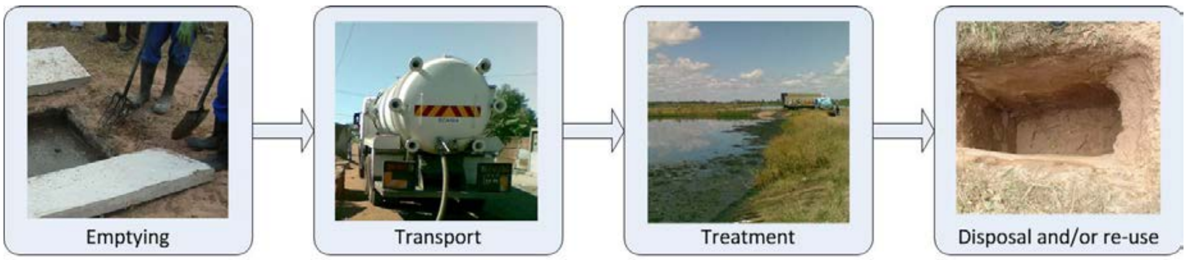

Figure 2.1: Basic faecal sludge management (FSM) chain (Cottingham 2011)

Many choices exist at each stage of the chain, with their suitability (technical, social and economic) dictated by the context. This project specifically focuses on the comparison of three options – the LaDePa process, combustion and landfill - for the treatment and/or disposal/re-use stages. Little economic evaluation work appears to have been carried out thus far on the LaDePa and combustion processes as routes for faecal sludge disposal.

The emptying and transport processes are included in the model, firstly to enable a total cost comparison to be made between disposal routes, and secondly because these processes impact on the characteristics of the sludge ending up at the treatment/disposal site and therefore on the overall costs of disposal. Previous economic modelling work has been carried out on emptying and transport portions of the chain, and this study draws from that work.

The landfill disposal option was included in the study to provide a base case for comparison against the other two disposal options. Where faecal sludge cannot be buried on site, and no treatment option exists, hazardous landfill is one of the few safe alternatives – but is clearly costly.

This section provides further background to the LaDePa and combustion processes.

2.2 Background to the sludge disposal routes

This section provides an overview of the three disposal routes for pit latrine sludge that were included in the economic model. The two main routes analysed were the LaDePa process and combustion. Landfill was also included as an option to provide a comparative cost for what is effectively the 'do-nothing' off-site disposal route.

2.2.1 The Latrine Bio-solids Dehydration Pasteurisation (LaDePa) process

The LaDePa process was developed by eThekwini Water and Sanitation (EWS) in partnership with Particle Separation Solutions (Pty) Ltd (PSS) and piloted in eThekwini municipality (KwaZulu-Natal, South Africa). In response to thousands of on-site sanitation facilities with full pits across the municipality, EWS initiated a pit-emptying programme, with the service offered free to households once every five years. The volume of sludge requiring disposal is approximately 7 000 m^3 per year. 35 000 VIP latrines were emptied during first phase of this project with around 70% of the sludge produced buried on-site (where sufficient space existed) (Harrison & Wilson 2013 pers. comm., 4 March 2013). In the more densely-populated areas, sludge had to be transported off-site and processed elsewhere. The LaDePa process was developed as possible means of processing this sludge, reducing the quantity of solids that had to be sent to sanitary landfill and potentially creating a product with a market value.

Figure 2.2 illustrates the stages of the LaDePa process. Sludge removed from pit latrines consists of faecal sludge together with solid waste, including material used for anal cleansing (e.g. toilet paper, newspaper, plastic packaging) and other refuse (e.g. clothing, hair extensions, disposable nappies, sanitary pads, rope, bottles and cans). The LaDePa process separates the faecal sludge from the solid trash material by compressing the mixture in a screw compactor with lateral ports, through which the faecal sludge is extruded (Stage 1). The trash material exits from the end of the screw conveyer.

The sludge is deposited in a 25 to 40 mm thick layer of extruded cylinders (of 6 mm diameter) onto a porous moving steel belt. Hot exhaust gases from the plant's internal combustion engine pass upwards through the belt to pre-dry the sludge (Stage 2). The sludge is then further dried and pasteurised with medium wave infrared radiation (MWIR) under vacuum (Stage 3). The residence time of the sludge on the belt is 8 minutes (4 minutes subject to upward exhaust gas flow at 500 °C and 4 minutes under MWIR under vacuum at 750 °C) (Harrison & Wilson 2012, PSS nd).

A sterilised, pelletised product is produced with a typical solids content of 60% (dependent on the feed moisture content) (Harrison & Wilson 2013 pers. comm., 4 March 2013). The pellets contain organic matter, nitrogen (N), phosphorus (P), potassium (K) and micro-nutrients critical to plant growth.

Initial analysis of pellets produced from the process indicate lower levels of N, P, K and micro-nutrients than commercially-available fertilizers, but still of levels to be of benefit in land application (Plant Laboratory Analytical Services, KwaZulu-Natal Department of Agriculture 2011)[2]. More recent analysis showed the similar results (see Section 7.1). Informal growth trials undertaken in plant pots indicate good yields with application of LaDePa pellets compared to commercial fertilizers.

The pellets could be sold for application to agricultural land as a fertilizer and soil improver product. An alternative would be to use the pellets as feed for a combustion process, to further reduce the solids to be disposed of and potentially to recover energy.

[2] Note that the sludge processed for the pellets that were analysed had been stored for several years after removal from the pit, therefore significant nitrogen loss might have taken place. Systematic sampling of several batches of pellets will be required to determine useful values for average nutrient content.

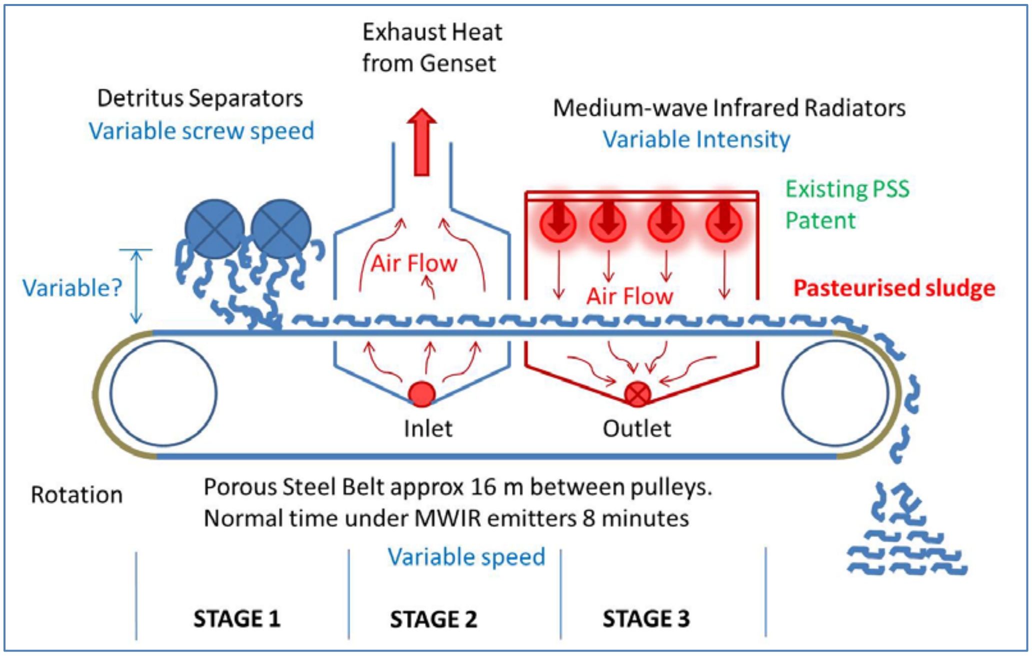

Figure 2.2: Schematic of the LaDePa process (Modified from Harrison and Wilson, 2012)

2.2.2 Combustion

A total combustion process reduces sludge volume through the oxidation of organic matter to carbon dioxide and water. Energy may be recovered from the process. Pathogens are destroyed. The ash product may contain significant levels of nutrients. Partial combustion processes, e.g. pyrolysis, are not covered in this study.

The original plan for the combustion section of the model was to make use of data from a fluidised bed incinerator used at a local wastewater treatment works (KwaMashu wastewater treatment works in eThekwini municipality, South Africa) to incinerate primary sludge. However, it proved to be difficult to obtain any operational data on the incinerator due to confidentiality reasons, and therefore the majority of the data used to populate this section of the model was taken from literature and from limited analysis of the incinerator feed sludge and the ash produced.

A fluidized-bed reactor (FBR) is installed at the KwaMashu wastewater treatment works to incinerate de-watered sewage sludge at 850°C. The plant is owned by the eThekwini Municipality and currently managed by Coal and Waste Utilisation (Pty) Ltd. The sludge incinerator and dryer plant was first commissioned in 2000 and was designed to incinerate 80 t/d (at 35% solids) of raw sludge in a fluidized bed reactor (FBR) and dry 100 t/d (at 18% solids) digested sludge/waste activated sludge mixture in a spouting bed dryer (SBD). The incinerator and the dryer were designed to complement each other, by using the hot combustion gas from the incinerator to dry digested sludge into pellets. The pellets are then fed to the incinerator as a supplementary fuel since the calorific value of the wet raw sludge is insufficient to maintain the bed temperature at 850°C (Botha et al, 2011).

Due to a number of operational problems, the plant was shut down and re-commissioned at the end of 2002 with the addition of a regenerative thermal oxidizer (RTO) to remove odour from the exhaust gases. Figure 2.3 is a process flow diagram of the FBR facility (Botha et al, 2011).

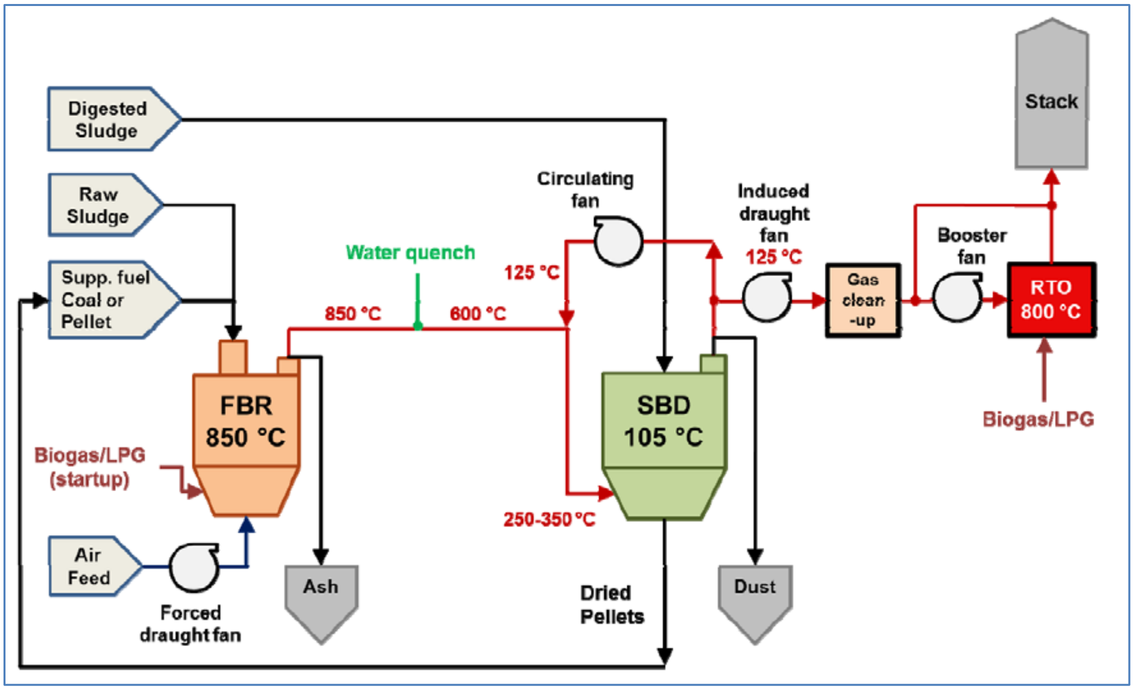

Figure 2.3: Schematic of the Fluidised bed reactor at KwaMashu Wastewater Treatment Works (Botha et. al 2011)

There are a number of advantages and disadvantages to the use of a FBR in the incineration of sewage sludge. Advantages include the complete combustion of organic compounds, a 90% reduction in sludge volume and the destruction of pathogens. However, the process produces large quantities of fine ash which is difficult to remove unless water is added to produce a slurry. At this stage the wet ash from the incinerator is allowed to settle, the water collected and recirculated to the head of the wastewater treatment works and the ash collected in skips.

Modelling of sludge pre-treatment and combustion can occur at various levels of complexity:

i) Sludge drying with external energy source and combustion;
ii) Sludge drying and combustion with energy integration (exhaust gases from combustion are used to dry the sludge);
iii) Introducing co-combustion with other fuels;
iv) Conversion of sludge to 'green coal' and use / sale of product as a power plant fuel[3]

The current version of the model was based on scenario (i), use of a small, local incinerator with no energy recovery or electricity generation. Increasing the scale of the plant and incorporating either of these measures would have a significant impact on the economics of this disposal option.

Significant costs for combustion are associated with environmental permitting, air pollution control devices and emissions monitoring. Another potential additional cost when burning sludge is the requirement for supplemental fuel during start-up and potentially to maintain incinerator temperatures if the energy content of the feed sludge is insufficient.

Various options were considered within the model for the end use and/or disposal of the ash product:

- Addition to LaDePa pellets or other fertiliser product as a nutrient source;
- Disposal to general landfill;

[3] See the FaME project (EAWAG and Waste Enterprisers) in Ghana.

- Production of construction materials, e.g. bricks and cement.

It should be noted that because the combustion section of the model is currently based primarily on literature figures, it does need further development, and the results produced are unlikely to be as accurate as those calculated for the LaDePa and landfill disposal routes.

2.2.3 Disposal of sludge to landfill

The disposal of pit latrine sludge to landfill is not a preferred option in South Africa due to high costs, diminishing landfill availability, wasted resources contained in the sludge, and the environmental burden of landfill sites (disposal of material to landfill is strictly regulated in South Africa). Hazardous landfill to an existing facility is however the simplest 'safe' option for off-site disposal of faecal sludge as it requires no new facility to be built and operated. It has been considered as a third disposal option in the model to provide a cost comparison against the LaDePa and combustion routes. The landfill route costs the emptying of pits, conveyance of sludge, and landfill fees.

2.3 General comparison of disposal routes

Table 2.1 provides a general comparison of the benefits and disadvantages of the LaDePa, combustion and landfill processes, to provide context to the detailed economic comparison.

The objective of this study was to carry out a whole-life economic evaluation of these disposal routes. A holistic comparison of disposal methods needs to take both the financial costs/benefits of disposal as well as factors that cannot be monetised into account. However, since the focus of this study was the development of an economic model, it does not make a detailed analysis of the non-monetisable factors.

They may include:

- Impacts on quality of life of residents near the sludge processing plant;
- The creation of different types of jobs (e.g. an incinerator may create opportunities for higher-skilled labour but the LaDePa plant may provide more opportunities for training local unskilled labour – still to be determined);
- Wider environmental impacts where potential nutrients available from sludge are not utilised, and a higher quantity of conventional fertilizer is imported to the area and used instead;
- Land constraints;
- Local availability of other feed streams for co-treatment with faecal sludge;
- Local attitudes to reuse of faecal sludge products in agriculture.

The following sections of the report describe the process for the development of the economic model.

Table 2.1 Comparison of benefits and disadvantages of the LaDePa and Combustion processes and landfill for the disposal of faecal sludge

	LaDePa	Combustion	Landfill
Benefits	Reduction in water content from ~70% to ~40% - solids volume reduction of 50% [4]	Solids volume reduction of ~90% (VWS 2013)[5]	Existing facilities can be used – no requirement for construction and operation of new technologies.
	Reduction of solids to be sent to landfill (20% of feed to process)[4]	Pathogen inactivation and destruction of toxic compounds	
	Pathogen inactivation	Potential for energy recovery.	
	Integrated trash material (non-organic solids) removal	Potential use / sale of ash for the production of commercial products (e.g. brick production).	
	Production of potentially saleable product for agricultural land application – significant C, N, P, K content.	Potential land application of ash product (nutrient content to be determined).	
	Production of a pre-dried, sterile feedstock for combustion which can be easily handled (manual unskilled labour).	Use and market for ash in construction products is established.	
	Local job creation if smaller-scale mobile plants are deployed.		
Disadvantages	Potential requirement for air pollution control device (to be determined by environmental impact assessment currently in progress).	Potential presence of odour-causing compounds, metals, organic pollutants (PAHs), dioxins and furans in both air emissions and ash; consequent requirement for air pollution control devices.	Costly, particularly for wet sludge (charged by mass).
	Nutrient content (N, P, K and micro-nutrients) cannot be closely controlled – may reduce value and/or reduce the potential market for the product. To be further researched.	Product may contain nutrients of use in agricultural applications, but will contain minimal carbon content compared to LaDePa pellets. To be further researched.	Diminishing landfill availability and stricter legislation on disposal to landfill.
	Little market research carried out for pellet product.	Requirement for treatment of waste streams from air pollution control devices.	Wasted resources (nutrients and energy) in the sludge.
	Disposal of sludge-contaminated detritus to hazardous landfill still required.	Probable requirement for additional fuel source during start-up phase and potentially to maintain incinerator temperatures during normal operation (dependent on energy content of sludge).	Leachate management is a significant challenge. Where not managed effectively, environmental damage will still occur.
		Possible greater public opposition to local presence of an incineration facility.	
		Product may require more specialised solids-handling than a pelletised product.	

[4] Harrison & Wilson 2013 pers. com., 4 March 2013
[5] VWS 2013

3 Economic model development and structure

This section of the report describes how the economic model was developed, describes its general structure, and provides a more detailed description of each module of the model. Supporting flowcharts are given in Appendix 6. Guidance on how to use the model is given in Section 4 of the report.

3.1 Model development and general structure

The following iterative process was used to develop the model:

1) Review of any previous work that modelled any part of the proposed system.
2) Listing of the required inputs and outputs for each module of the model. Review and summary of the data currently available to populate the model.
3) Further research to find or estimate missing input data.
4) Development of first version of model; population of model with eThekwini municipality (South Africa) data.
5) Review of model structure and outputs with experienced practitioners; model refinement; addition and/or removal of modules.
6) Population of model with data from Dakar, Senegal. Review and further refinement of structure.
7) Sensitivity analysis.
8) Refinement and addition to model in areas indicated as critical or in error by sensitivity analysis.

Progress report from Phases 1 – 4 (see Appendices 1 to 5) describe in detail the work carried out at each stage of the model's development. A summary is given here, together with a description of the structure of the final version of the model.

The economic model was developed as a series of interrelated modules, some of which were common to the three sludge disposal routes under analysis. Figure 3.1 outlines the basic structure of the model and shows the linkages between modules.

The removal of sludge from pits and its conveyance (Modules 1 – 3) are required for all three disposal routes. The characteristics of the sludge to be disposed of will depend both on the properties of the sludge in the pit and how it is handled en route to the processing/disposal site. The characteristics of the sludge may impact on what disposal route is chosen, and the efficiency of treatment via that route. The properties of sludge collected from pits in one area (e.g. with high groundwater, causing wetter sludge) might make one disposal route more economically viable than another. Therefore although pit-emptying and conveyance are common to all three the disposal routes, it is important to test how the relative economic viability of the three routes changes in response to how pit-emptying and conveyance is carried out.

After the Conveyance stages, the model splits into modules relating only to LaDePa (Modules 4 – 9), combustion (Modules 11 – 16) or landfill (Module 17). Sludge storage facilities prior to pre-treatment and processing are costed for at the LaDePa and combustion sites, whilst it is assumed that sludge is taken directly to landfill with no intermediate storage.

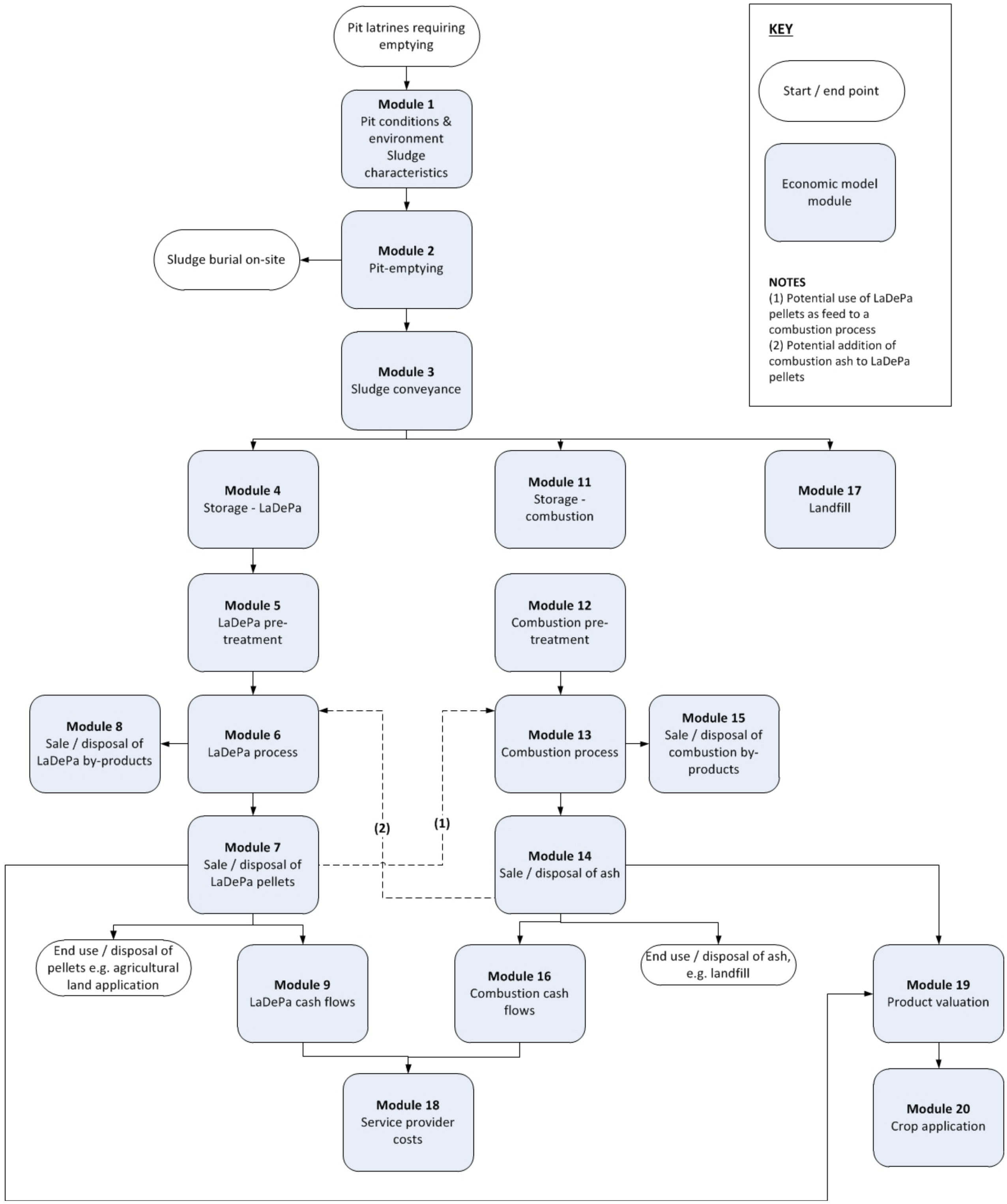

Figure 3.1 General structure of the economic model of sludge disposal routes

The LaDePa and total combustion processes may be linked if the product from one process is used as the feed to the other, via

(i) LaDePa pellets being used as a feed to an incinerator – a pre-dried, easy-to-handle feed that could potentially be used in a fluidised bed combustor or
(ii) Combustion ash being added to the feed to the LaDePa pellets – ash could be used to adjust the water content of the feed to appropriate levels.

These routes are shown in Figure 3.1 and have been considered briefly within the model.
.
Module 18 accounts for costs incurred by the provider of sanitation services – often a local government department. Modules 19 and 20 calculate the possible economic value of the sludge products from the LaDePa and combustion processes.

Values for the majority of inputs are required to enable the model to function correctly. A '*Reference values' worksheet* is provided in the model as a guide to reasonable values for selected input parameters. Datasets for two different regions are also provided.

Each module calculates the change to sludge properties that occur over that stage of the FSM process, for example, the change in the sludge dry solids content when water is added during conveyance. Each module also calculates the capital and operating costs and revenues associated with that stage of the process. The costs and revenues are compiled in cash flow sheets for LaDePa, combustion and landfill. A levelised cost per pit, C_P, is calculated as follows:

$$C_P = \frac{\sum Discounted\ cash\ flows}{\sum Number\ of\ pits\ emptied}$$

Similarly a levelised cost per tonne of dry solids removed from pits, C_T, is calculated using:

$$C_T = \frac{\sum Discounted\ cash\ flows}{\sum Total\ mass\ of\ dry\ solids\ removed\ from\ pits}$$

The net present value (NPV) and internal rate of return (IRR) of the discounted cash flows are also calculated for each disposal method. These figures are the measures of the economic viability of the disposal methods.

Each of the modules is described in further detail below. Flow diagrams summarising the calculation structure of selected modules are given in Appendix 6.

3.2 Detailed model structure

The following sections provide details on each of the Modules and are divided as follows:

- Modules common to all disposal routes,
- Modules specific to the LaDePa, combustion or landfill, and
- Modules related to the valuation of the end product.

3.2.1 Modules common to all disposal routes

Module 1 – Pit conditions
The first section of the model asks for user inputs relating to the number of households, sludge accumulation rates, sludge characteristics in the pit and the pit-emptying arrangements for the area. It outputs the volume of sludge to be removed from an area per year and the physical characteristics of that sludge.

Module 2 – Emptying and ***Module 3 - Conveyance***
These modules together model the removal of sludge from the pit and its conveyance to the LaDePa or combustion site, or a central point from where it is taken to landfill. Figure 3.2 shows the conceptual geographic context that the model is based on, and the distances that are user-inputs to the model. The pit-emptying sub-contractor is assumed to have a base with storage and cleaning facilities for equipment at a distance ***E1 km*** from the residential area where pits are to be emptied. Within the pit-emptying area, the pits to be emptied on any given day are an average distance ***E2 km*** from one another. This distance is not necessarily the distance between neighbouring houses, as pits may not be emptied sequentially along a particular street.

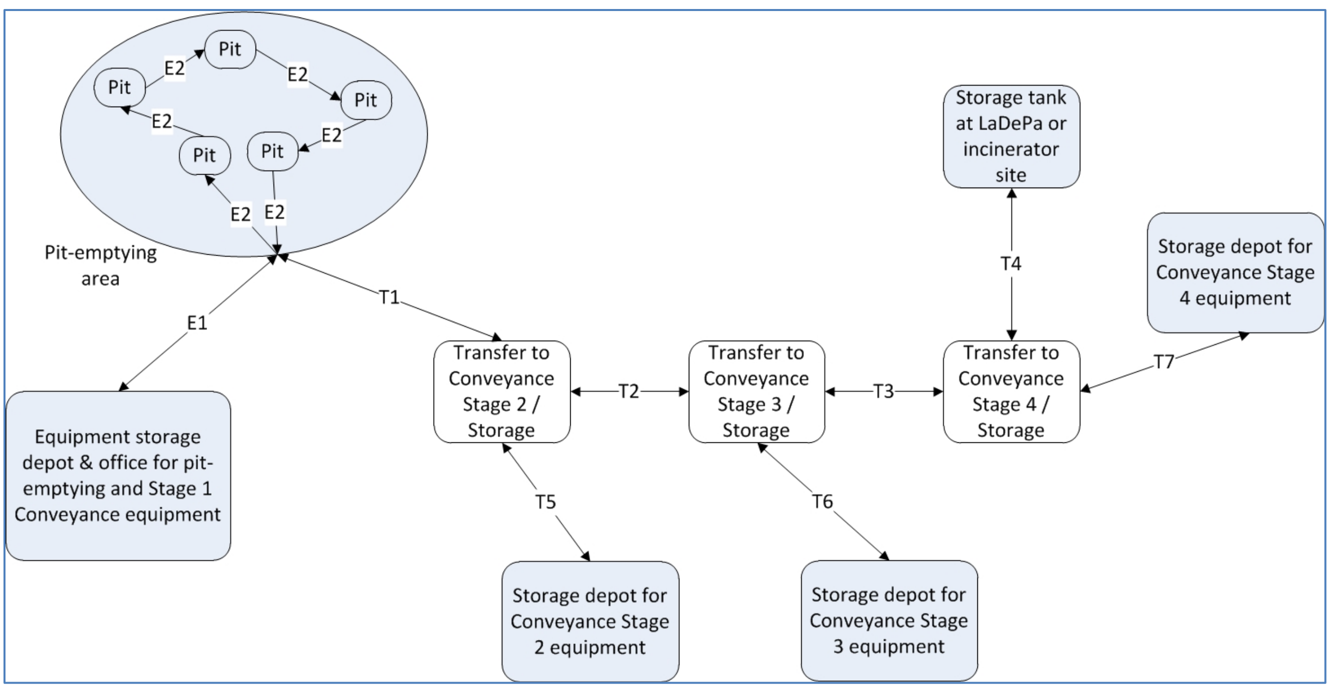

Figure 3.2 Schematic of the model geography

The user chooses one of the following emptying methods, and enters the required operational and input data for that method:

1) Manual emptying: this may be using only buckets and shovels, or may also incorporate the use of a small pump (manual, such as the Gulper or externally powered, such as the e-Vac);
2) Small vacuum tanker: examples include the Vacutug, Honeysucker and Maquineta;
3) Large vacuum tanker: conventional tankers with volumes of around 10 – 14 cubic metres.

The conveyance of sludge from the pit to the disposal site can be carried out over one or several stages. This allows for different types of vehicle to be used for different portions of the journey. For example, sludge might be conveyed in containers on a handcart through narrow passages and then transferred to a pick-up truck on reaching a road. An intermediate storage tank can also be used for one 'stage' of the journey. The distance between the pit and the disposal site, or the changeover point to the second form of sludge transport used is ***Stage 1*** of the conveyance sequence, and occurs over a distance ***T1***. A second form of transport carries the sludge over a distance ***T2***, and so on, up to a maximum of four conveyance stages.

An example of a typical Conveyance sequence is given in Figure 3.3.

Figure 3.3 Example of a typical conveyance sequence for faecal sludge

The Conveyance module offers the following choices of conveyance options:

1) Handcart carrying containers of sludge;
2) Pick-up truck carrying containers of sludge;
3) Motorised transport – small vacuum tanker (e.g. Vacutug);
4) Motorised transport – large vacuum tanker
5) Transfer station – underground holding tank (which must be later pumped out);
6) Sewer discharge station (SDS) – connection to sewer where both solids and liquid discharge to sewer, large detritus is screened out;
7) Septic tank discharge station – liquid effluent connection to sewer, solids accumulate in the tank and are periodically pumped out, large detritus is pre-screened out.

The model is designed to limit the user to 'allowable' combinations of Conveyance options. For example, where the manual pit-emptying method has been chosen, Conveyance Stage 1 must be a handcart or a pick-up truck. Similarly, where the emptying method is a small or large vacuum tanker, Conveyance Stage 1 will automatically be the same as the emptying method. Costs and revenues for Conveyance Stage 1 are including within the Emptying module.

Each conveyance stage may be carried out by a different operator – e.g. a small informal business hand-carting sludge to a storage tank. A larger private business, or the municipality, might operate the intermediate storage tank and the vacuum tanker used to empty it. Stages 2, 3 and 4 of conveyance in the model will therefore each produce their own set of costs and revenues.

The user selects the Conveyance methods to be used at each stage, and enters the operational and financial inputs associated with these methods. The model will then calculate the costs associated with each Stage, dependent on the distances travelled and the volume and properties of the sludge to be conveyed. The model also calculates any changes in the properties and volume of sludge sent to final storage.

Module 18 – Service provider costs

The service provider costs are an additional percentage applied to the total costs calculated for each disposal method. These costs mainly account for the time required by the sanitation service provider (e.g.

the municipal government) to manage the provision of sanitation services where external companies are employed for implementation.

3.2.2 LaDePa process modules

Module 4 – Sludge storage for LaDePa

This module calculates the cost of storing sludge at the LaDePa site. The storage tank could be a permanent structure or temporary tank, depending on the nature of the sludge-processing operation. The storage facility may provide several days or weeks of buffer storage, or simply be a transfer point for incoming sludge going to pre-treatment.

Module 5 – LaDePa pre-treatment

Module 5 calculates the cost of pre-treating feed sludge from the storage tank prior to being processed by the LaDePa plant. The LaDePa process will not function properly if the feed sludge is too wet or too dry, contains large-size detritus or potentially if it has a high sand content (to be confirmed). This Module also calculates the changes to sludge properties that occur over the pre-treatment process and therefore the final quality of the blended sludge fed to the LaDePa plant. Further testing needs to be undertaken on the LaDePa plant in order to determine the acceptable range of water, detritus and sand content in the feed to the process. The current options being considered for pre-treatment are (i) water addition, (ii) water removal via drying beds, (iii) detritus removal and (iv) blending of sludge with additives.

Module 6 – LaDePa process

This module calculates the cost of treating faecal sludge via the LaDePa process and producing the pelletised product. It includes inputs for the LaDePa plant operational parameters (including volumetric throughput, belt speed, fuel usage and product dry solids), and capital and operating costs. Where possible, the operational parameters are linked to sludge throughput rate and the quantity and quality of the pellet produced, and therefore to the economics of the operation. This was however not possible for all parameters, as further work is needed in order to quantify the relationship between various operating variables and the operational costs of the process.

Module 7 – LaDePa product

Module 7 calculates the costs and revenues associated with the possible end-uses of LaDePa pellets. Costs include the cost of packaging the product, fertiliser registration costs (if applicable) and cost of transport to the end user. Revenues are calculated using product sale prices that are selected by the user in Module 20 (based on product valuation calculations). The end-use routes considered are:

- Sale at wholesale rates to agricultural users;
- Bagged sale to garden centres;
- Landfill;
- Feed to an incineration process.

Module 8 – LaDePa by-products

This module calculates the cost of disposing of the two by-product streams from the LaDePa process: detritus that cannot pass through the plant and the off-gas emissions from the plant. The disposal of detritus may be at a hazardous landfill or an incineration plant. Further detail is required on the regulations and costs associated with the emission of off-gases from the plant. An environmental impact assessment (EIA) is currently underway and will provide further data to feed into the model at a later stage.

Module 9 – LaDePa cash flow sheets
This final module for the LaDePa economic assessment uses the costs and revenues determined in Modules 1 -8 as inputs to a cash flow sheet and calculates the following values for the overall process of pit-emptying and sludge disposal using LaDePa:

- The levelised cost per pit;
- The levelised cost per tonne of dry solids removed from pits;
- The levelised cost per wet tonne of LaDePa pellets;
- The net present value;
- The internal rate of return value.

3.2.3 Combustion modules

Module 11 – Sludge storage for combustion plants
This module calculates the cost of storing sludge at the combustion plant site. The storage facility may provide several days or weeks of buffer storage, or simply be a transfer point for incoming sludge going to pre-treatment. The nature of the tank (temporary tank or permanent fixture) and cost will vary according to the storage volume required.

Module 12 – Combustion pre-treatment
Module 12 calculates the cost of pre-treating feed sludge from the storage tank prior to being processed by the combustion plant. The user inputs the acceptable limits for the properties of the feed stream to the combustion process. The main parameter of interest is the sludge dry solids content, as a feed that is too wet will result in the use of a prohibitive quantity of supplementary fuel. A limit on the feed detritus (non-organic) content of the combustion feed can also be entered, and costing for a detritus-removal stage included. The costs associated with a pre-treatment stage to blend an additive with the sludge – for example a component to raise the overall calorific value of the feed stream, or a different sludge stream requiring disposal – can also be included if required. The model calculates the changes to sludge quantity and properties over the pre-treatment processes and outputs the quality and flow rate of the feed stream to combustion, as well as the costs associated with pre-treatment.

Module 13 – Combustion process
This module calculates the cost of treating faecal sludge via a fluidised bed combustion process and to produce an ash product. It includes inputs for the combustion plant operational parameters, and capital and operating costs. The feed dry solids of the sludge are used to calculate the minimum required calorific value of the feed to the combustion plant. Where this is not supplied by the sludge alone, the quantity and cost of supplementary fuel required (type of fuel chosen by the user) is calculated by the model. Where possible, the other operational parameters for the combustion plant are linked to feed quantity and quality and to operational costs, but further work is required to refine these relationships. It should also be noted that different types of combustion process must be modelled independently – the costs of using a fluidised bed type furnace will be significantly different to, for example, a multiple hearth furnace.

Module 14 – Combustion product
Module 14 calculates the costs and revenues associated with the possible disposal routes or end uses for the ash. This includes the cost of packaging the product, product registration and of transport to the end user (if applicable). The end-use or disposal routes considered are:

- Addition to fertiliser products or land application;
- General landfill;
- Addition to construction materials, e.g. bricks.

Module 15 – Combustion by-products
This module calculates the cost of disposing of the non-combustible detritus and air emissions from the combustion plant. Sludge-contaminated detritus must be discharged to a hazardous landfill. Further detail is required on the composition of the incinerator off-gases from burning pit latrine sludge and the cost of the air pollution control devices that would be required. Costs will also be dependent on the locally-applicable legislation.

Module 16 – Combustion cash flow sheets
This final module for the combustion economic assessment takes the costs and revenues from Modules 1 – 3 and 11 - 15 as inputs to a cash flow sheet and calculates the following values for the overall process of pit-emptying and sludge disposal using combustion:

- The levelised cost per pit;
- The levelised cost per tonne of dry solids removed from pits;
- The levelised cost per dry tonne of combustion ash;
- The net present value;
- The internal rate of return value.

3.2.4 Landfill module

Module 17 – Landfill cash flows
The landfill disposal route calculates the applicable emptying and conveyance costs from Modules 1 – 3, as for the other two disposal routes. The costs of additional transport to the landfill site and gate fees are calculated and entered as an input into cash flow sheets. The following values are provided as outputs:

- The levelised cost per pit;
- The levelised cost per tonne of dry solids removed from pits;
- The net present value;
- The internal rate of return value.

3.2.5 End product valuation modules

Module 19 – Product valuation
The possible market value of the LaDePa pellets and combustion ash as agricultural products are calculated on the basis of their nutrient content and the sale prices of other fertilisers on the market. The value of the LaDePa pellets as a feed to combustion is calculated based on its calorific value and dry solids content. No valuation calculation is currently included for use of ash in construction materials as further research is required in order to quantify this.

Module 20 – Crop application of sludge endproducts
This module considers the economic viability of using LaDePa pellets to fertilise a specified crop in place of commercially available inorganic and organic fertilisers. A partial budget analysis is used, based on supplying the crop's demand for a user-specified nutrient (N, P or K). The transport and spreading costs of each of the products is also calculated, and this is linked to the quantity of each product required. The model outputs the maximum price that the LaDePa pellets could be sold at to be able to compete with commercially available fertilisers.

The various product values and selling prices are compiled into a table. The user selects the appropriate selling price for LaDePa pellets and combustion ash, which are then used to calculate the revenues from product sales in Modules 7 and 14.

Note: the partial budget analysis is not done on ash, only LaDePa pellets. It is assumed that ash could be used as an additive, but not as a standalone product.

4 Using the model – overview

Detailed instructions on how to use the model and guidance on the specific inputs are given within the model itself. This section provides a general overview of the layout of the model, how model cases are set up, and notes on the capability of specific sections of the model.

The nomenclature used throughout the model has been selected, where possible, to match the terms used in the 'Compendium of Sanitation Systems and Technologies' (Tilley et al 2008).

4.1 Model worksheets

Table 4.1 summarises the list of worksheets contained within the model spreadsheet, their functions, and the level of user-modification allowed.

Table 4.1: Summary of worksheets within the model

Sheet name	Function	Edit status
Cover	Model basic information, list of worksheets, list of revisions and revision status	**Locked aside from model user revisions section**
Notes	General instructions on model use	**Locked**
MAIN MENU	Navigation sheet – graphic of model structure with links to worksheets	**Locked**
INPUTS	Inputs sheet. All model inputs **must** be entered and modified through this sheet. Input cells highlighted in blue.	**Blue input cells can be modified. 'References' and 'User notes' columns can be edited. All other cells locked.**
Results LCU	Main model outputs, given in local currency units (LCU)	**Locked**
Results USD	Main model outputs, given in US dollars (USD)	**Locked**
Rates	Summary of standard rates and inputs used throughout the model	**Locked**
Worksheets "1.1 Pit conditions" through to "Lists"	Model calculation sheets. Full list given in Appendix 7.	**Locked**
G1 Distances	Graphic showing the conceptual geography the model is based on, and the distances that the inputs sheet refers to.	**Locked**
Abbreviations	List of abbreviations used in the model	**Existing entries locked, but additions to list allowed**
Typical values	List of typical values for some of the input parameters, to provide a suggested value when the value for an input parameter is not known.	**Locked**
References	List of literature references referred to in the model.	**Existing entries locked, but additions to list allowed**
Cost analysis	Automated sensitivity analysis – in development	**Locked**
Cost analysis chart	Graphed results of the sensitivity analysis – in development	**Locked**

4.2 Model navigation

Figure 4.1 and Figure 4.2 show two screen shots of the model Main Menu page. This page gives a graphical summary of the model structure, and provides links to all the model sheets. The menu sheet also appears at the top of each model worksheet.

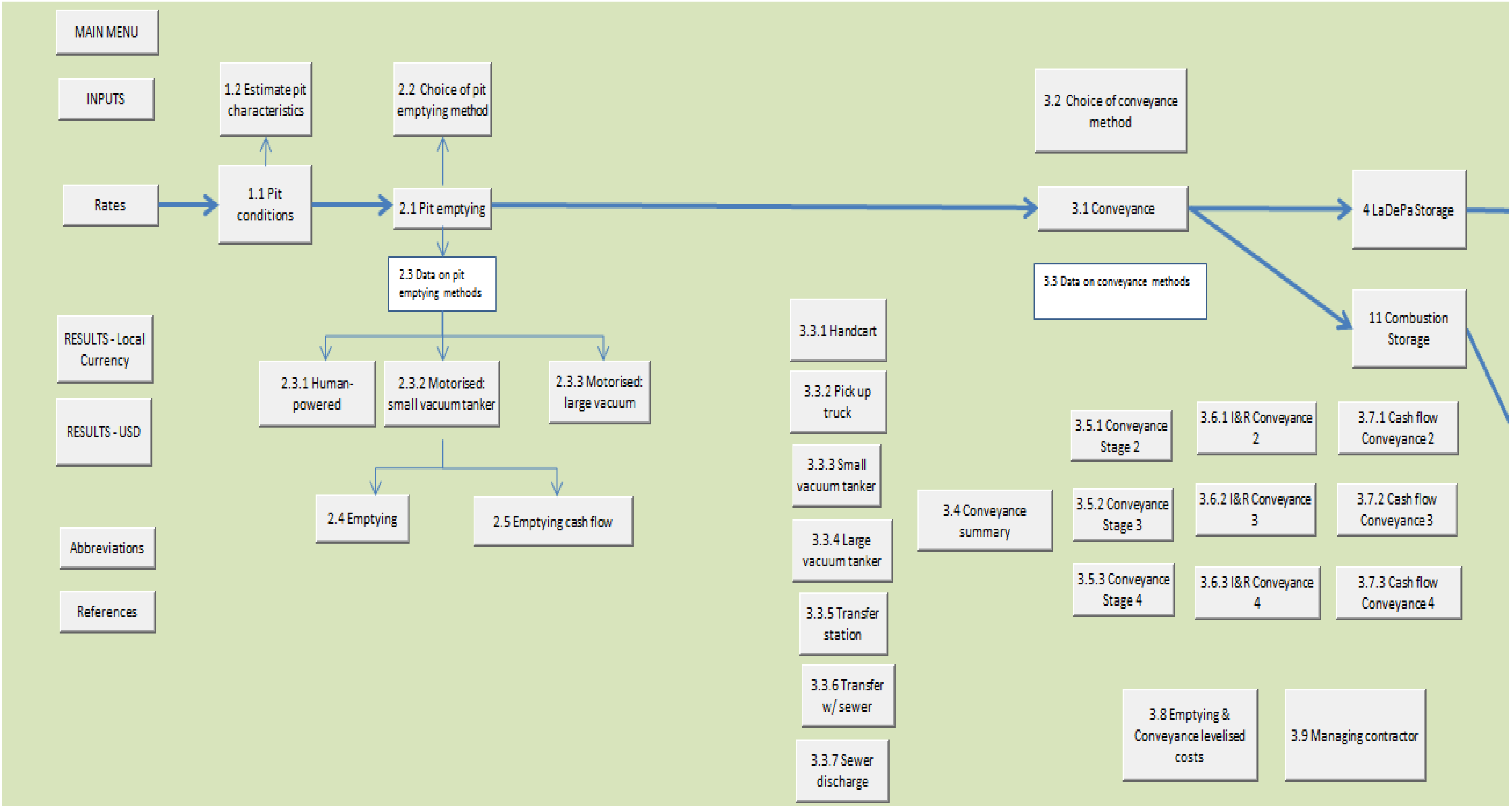

Figure 4.1: Screenshot of main menu page of model (Part 1)

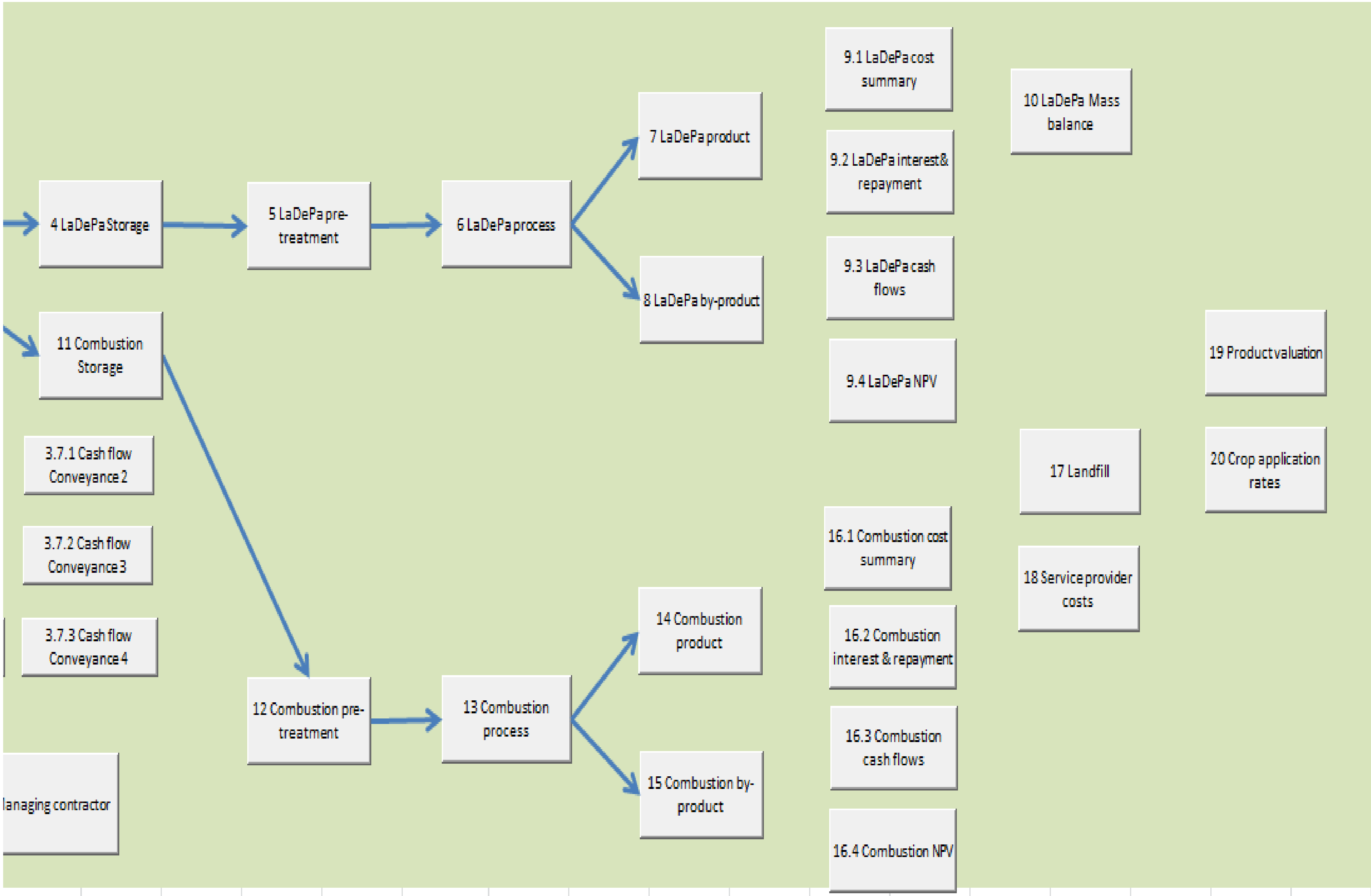

Figure 4.2: Screenshot of main menu page of model (Page 2)

4.3 Model format

4.3.1 Colour codes for cells

Table 4.2 gives the key to cell colours used in the spreadsheet model.

Table 4.2 Key to colours used in spreadsheet cells

	Input (blue)	Input cell. On the INPUTS sheet these cells can be modified. On other sheets these cells cannot be modified, but they indicate where a value is linked back to the INPUTS sheet.
	Optional input (blue, with orange in column A)	An input included for information only
	Inputs requiring review (blue, with red in column A)	Inputs that may require modifications after the first model run.
	Linked value (grey)	Value carried from another part of the spreadsheet
	Calculation (white)	Calculation cell – cannot be modified
	Check (yellow)	Indicates a query – user required to check a value.
	Example (green)	Example given – cannot be modified.
	Error (red cell)	Highlighting where an input is incorrect and needs to be checked

4.3.2 Model inputs

Input values for the model can **ONLY** by entered or modified via the **INPUTS** sheet. The values entered on this sheet are linked through to the different model pages. The input cells where values can be entered are coloured blue, as shown in Table 4.2.

Compulsory inputs
Most inputs are required to enable the model to function correctly. Where a value is not known for a particular context, an estimate should be made. The user can refer to the 'Reference values' worksheet in the model for a guide to reasonable values for unknown parameters, or to datasets given for other regions.

Optional inputs
Some inputs are included at this stage for information only and are not linked to model calculations. These inputs are indicated as 'optional' by orange highlights in column A of the spreadsheet.

Inputs for review
It is expected that an initial set of inputs will be entered, the model run, and the inputs then revised and the model run again. When an input is modified, there are various inputs that may also require modification as a result, for example, the number of LaDePa plants chosen to be in operation. These inputs that must be reviewed for accuracy when modifications to the model have been made are highlighted in red in column A.

Error checks
There are several inbuilt error checks that will highlight an ‘error check’ cell in red if user intervention is required. Errors normally arise where the model detects that an input is out of the required range. For example, the model calculates the number of machine days required for a particular operation. The user inputs the number of months that staff are employed (to allow the option for retaining staff full-time or only for the months that the process is operational). If the number of staff days required to operate the machine is lower than the machine days required, the model will raise an error and prompt the user to input a higher number of staff days.

Workaround sheets
The intention has been to make the model applicable to as wide a range of contexts as possible, however it is recognised that the format of inputs is unlikely to be ideal for all situations. Where a required input is not known, or is known with different units to those requested by the model INPUTS sheet, a workaround sheet should be created by the user to convert the known value to the form of input requested by the model.

The standard inputs the model requires can also be adapted to different contexts. For example, in eThekwini municipality pit-emptying teams are preceded by an advance team who open access to the pits. The model does not have the facility to specifically cost for an advance team, but as the two teams work concurrently the cost can be included simply by increasing the number of members per pit-emptying team.

User feedback is welcomed to allow future versions of the model to better reflect the inputs needed in different locations. The **‘User comments’** column on the **INPUTS** sheetprovides a space for notes on specific inputs to be recorded.

4.3.3 Inputs sheet structure

Table 4.3 shows the first few rows from the model **INPUTS** sheet. Parameter values are entered in the blue cells. Units may not be modified.

The source of the value is entered by the user in the ‘**Reference/source’** column, to allow for future users to identify where the data was obtained.

The ‘**Template notes’** column provides guidance on specific inputs. This column may not be edited by the user.

The ‘**User comments’** column allows the user to record additional information on any input.

Table 4.3: Sample inputs from the spreadsheet model, completed for the eThekwini Case Study

Location	eThekwini municipality, South Africa				
Date made	15/09/2013				
Rates					
Parameter	**Value**	**Unit**	**Ref / source**	**Template notes**	**User comments**
Financial					
Local currency	South African Rand	ZAR		Name and units are inputs	
Exchange rate local currency -USD	10	Local currency / USD			As on 1 Sep 2013
Escalation rate on O&M costs and revenues, excluding fuel	6	%		O&M = operating & maintenance	
Escalation rate on fuel	12	%		Often higher than escalation rate on other costs.	Average over last 5 years.
Interest rate on debt	9	%			
Debt proportion in debt: equity ratio	70	%			

4.3.4 Units

The section highlights points that should be noted with respect to the units used in the model.

Currency
All inputs entered on the INPUTS sheet are entered in Local Currency Units (LCU). Model calculations are carried out in LCU.

A conversion rate for LCU to US dollars (USD) is entered under the Rates inputs. The main results of the model are then given in both LCU and USD, on separate Results worksheets.

General
SI units are used throughout the model.

Units of dry solids content are given as %DS. This is the same as weight %, and is given by the following formula:

$$\%DS = \frac{Mass\ solids\ remaining\ after\ 24h\ at\ 105\ °C}{Initial\ wet\ mass\ of\ solution\ or\ suspension}$$

Therefore it must be noted that for high-solids sludge, the wet sludge density value is required in order to calculate the mass of dry solids resulting from a known volume of sludge with a known dry solids %. High-solids sludge (over a few %DS) cannot be assumed to have the same density as water.

Where ‘tonnes’ are specified, wet metric tonnes are implied, unless otherwise specified.

4.4 Business model basis

The model allows a certain amount of flexibility in the business model used for the faecal sludge management chain.

A major factor in defining the business model is identifying who is responsible for paying for sanitation services. Where sanitation is partially or completely paid for by government, the model will probably be used to calculate the costs at each stage of the FSM chain, to produce an overall cost of managing sludge in a particular area. Any revenues entered into the model will be those that go back to the financer of sanitation services, to offset costs.

Where the householder pays for the management of sludge, the business model is likely to be substantially different. Pit-emptying and sludge conveyance may be carried out as independent businesses from sludge treatment and disposal operations, and will normally be financed from pit-emptying fees paid by householders.

Treatment and disposal costs of sludge may not be covered by the fee paid by householders. Where a sludge disposal facility exists, pit-emptiers may pay a gate fee to discharge sludge, which then covers the operating costs of the facility. The cost is in this case passed back to the householder.

If the sludge treatment facility is able to produce a saleable product from the sludge, they may accept sludge for free, or even potentially pay for its delivery to site. Government may also choose to pay for sludge dumped at a treatment facility to incentivise safe sludge disposal. In this case the householder is not covering the whole cost of sludge treatment and disposal.

The following sections outline the general assumptions made in the model.

Pit emptying and sludge conveyance

Emptying and conveyance operations are carried out by one or several pit-emptying sub-contractors. A percentage is added on to the total costs of emptying and conveyance to account for this subcontractor(s)' mark-up rate.

The emptying and first stages of sludge conveyance are managed by a single operator. The first stage of conveyance may be set to zero km if no sludge conveyance is carried out by this operator.

The second, third and fourth stages of conveyance (whichever are applicable) may be handled by different operators. Cash flows for each conveyance stage are calculated on sheets 3.7.1 to 3.7.3.

The pit emptying and conveyance section of the model may be run as an independent model, to compare the likely costs of different emptying methods for a particular area. Inputs must be entered for all relevant methods. Levelised costs of each combination of methods are given on sheet 3.8.

Sludge processing via LaDePa or combustion

It is assumed that a managing contractor is appointed to manage the LaDePa and / or combustion operations. This includes a sludge reception/storage facility, pre-treatment processes, the main LaDePa or combustion plant, product packaging and storage, and by-product disposal.

The managing contractor may charge the sanitation service provider any or all of a site establishment fee, fixed monthly costs, and a percentage of all operating costs (excluding fuel costs).

Overall costs

The model calculated an overall cost per pit, cost per tonne of dry solids removed from pits, and cost per tonne of sludge product (pellets or ash) produced for the entire FSM chain. The user may choose to exclude the cost of pit-emptying and conveyance from the cash flow calculations if desired.

The model allows for costs of the sanitation service provider (e.g. a government department) to be accounted for separately. A fixed percentage of total costs is added to account for project management time. This cost can be set to zero if the FSM activities are all being run as independent private businesses.

Figure 4.3, Figure 4.4 and Figure 4.5 provide a summary of some of the various business options possible to simulate within the model.

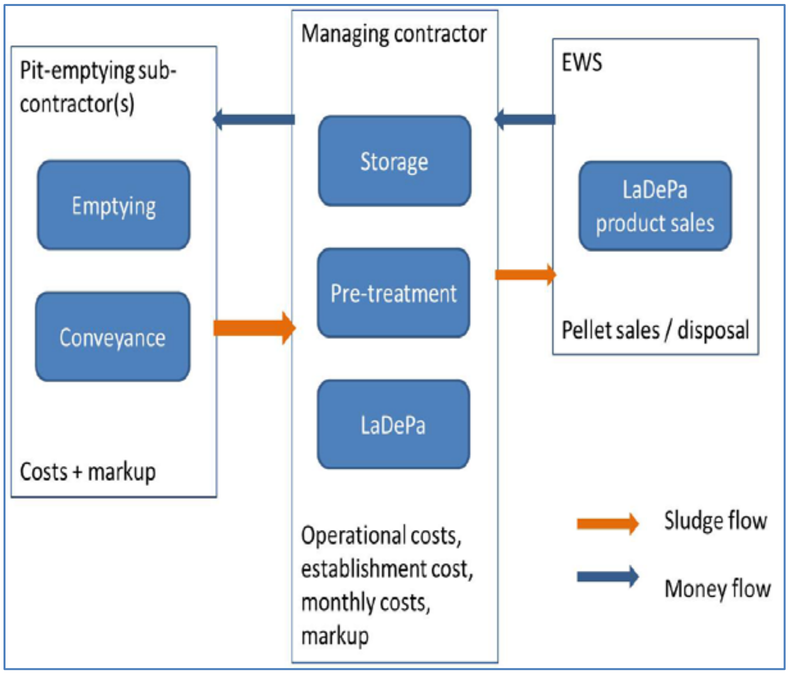

Figure 4.3 Business model option 1

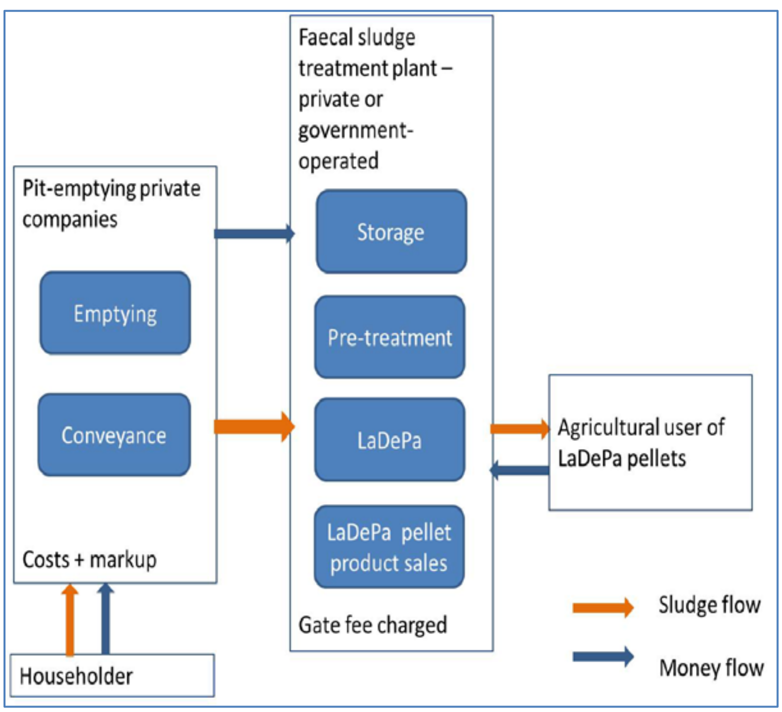

Figure 4.4: Business model option 2

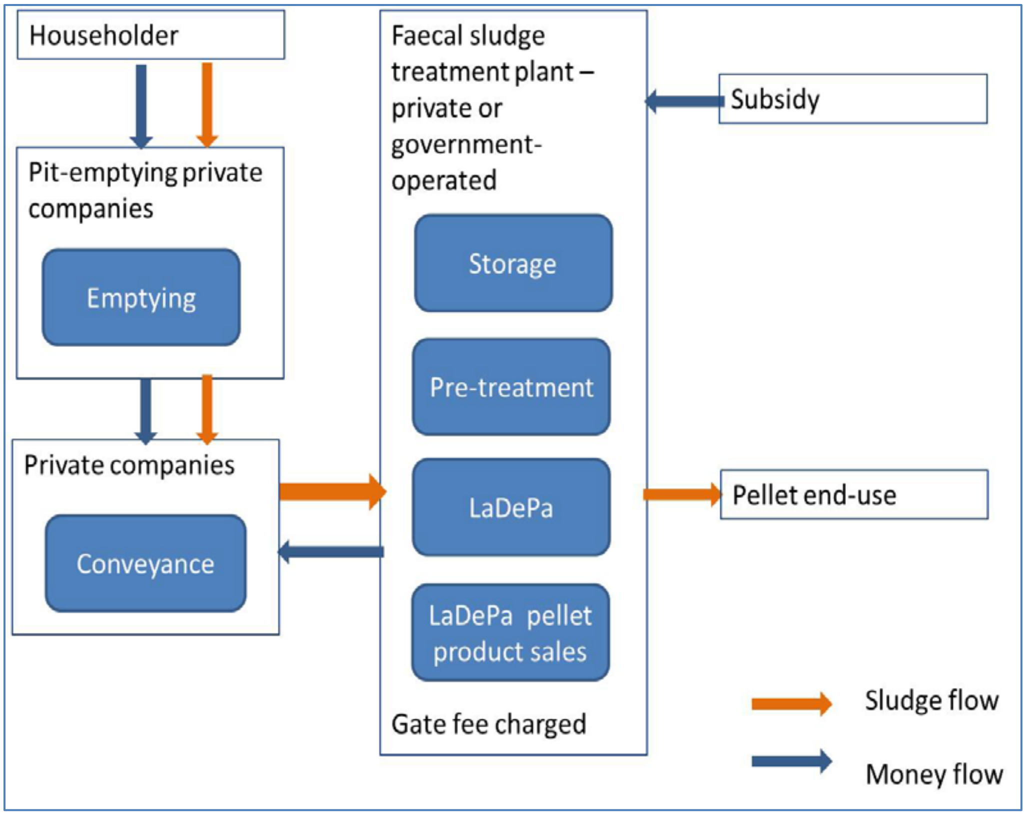

Figure 4.5: Business model option 3

4.5 Model case example

Normally only a proportion of the model inputs will need to be completed for a particular model case. This section briefly summarises the route through the Inputs section of the model for the eThekwini municipality case.

For the eThekwini case, manual emptying together with sludge conveyance by pick-up truck was selected. Figure 4.3 shows the corresponding route through the first 3 modules of the model.

From module 4 onwards, all modules must be completed to obtain the comparison between the three disposal routes and to carry out the product valuation.

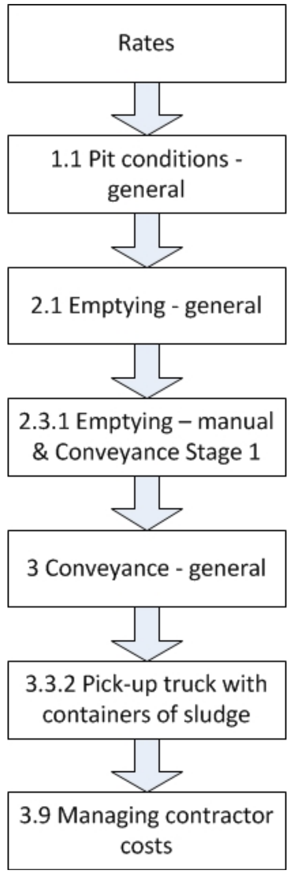

Figure 4.6: Flowchart showing progression through the inputs sheet

4.6 Model philosophy

When using the model, the following should be noted:

- It is unlikely that accurate values will be known for all the required inputs for a particular context. The strategy should be to make sensible estimates, referring to reference values where necessary. The sensitivity analysis included in section 6 of this report indicates those inputs where greater accuracy is of particular importance. Ideally a new sensitivity analysis should be undertaken for a new data set, using the method described in Section 6.

- It is expected that an initial set of inputs will be entered, the model run and the outputs reviewed and validated against any known values for the context. Section 6.1 gives suggested model outputs that can be used for validation.

- The review should include both the main outputs on the Results pages, as well as operational values calculated on individual model sheets, e.g. the number of pits it is possible to empty in a day. This should provide a sense-check on how well the model is simulating the context.

- It is likely that inputs will then need to be modified, and the model re-run, particularly where there was uncertainty over what value should have been assigned to them initially.

- Various iterations of the model will be run until the user is satisfied the model is running as close to reality as possible. The model can then be used to predict costs and test different scenarios for a particular context.

4.7 Incomplete model sections

The following sections of the model are still in development:

- **Section 1.2 Estimation of faecal sludge properties:** This section currently provides a list of questions to aid the user in considering what may affect the properties of the sludge in pits in their area. In a future version of the model it is intended that this section produces estimated properties of sludge based on the answers to these questions.
- **Section 2.2 Choosing the appropriate emptying method for the area:** The purpose of it is to provide the user with guidance as to the appropriate emptying method to use for their context, based on the geographical and social conditions. This section of the model has not been developed under the current scope of work.
- **Cost analysis and cost analysis chart:** The graph generation for sensitivity analyses is not currently automated. Users must run the model for different input values, record the corresponding outputs, and manually plot the required graphs.

4.8 Detailed notes on individual model sections

There are a number of detailed aspects that need to be taken into account with regard to the capacity and limitations of the different model sections. This includes information on the following modules: Rates, Pit conditions, Emptying, Pre-treatment, LaDePa, Combustion, End products, By-product disposal and Results.

A full list is provided in Appendix 8 and can be used as a reference check if detail on the calculations, assumptions or limitations behind a particular section of the model is required.

5 Economic model input parameters

The following sections provide an overview of the model input data obtained for two locations: (i) eThekwini municipality, Durban, South Africa and (ii) Dakar, Senegal. It was important to collect and analyse this data to develop a model that accounted for all relevant inputs (as far as possible), and to validate the model by checking the calculated outputs against known actual costs.

A list of input and output parameters were compiled for each module of the model as was shown in Figure 3.1. Data was obtained from a number of sources, and where no data existed estimates were made based on literature.

Sources that were reviewed included:

- Previous FSM economic models that have focused on some modules in the proposed economic model;
- Published literature data;
- Information from eThekwini Water and Sanitation (EWS) staff and reports;
- Information form partner organisations carrying out FSM work, including SANDEC/EAWAG;
- Operational information from industries running similar processes on feeds other than VIP sludge, e.g. sewage sludge incineration operations;
- Laboratory analysis of sludge, ash and pellets.

A full list of reference material is provided in the Reference section of this report.

The input data can be broadly grouped into the following:

(i) Data relating to physical sludge characteristics, e.g. dry solids content. This has a significant impact on the economics of the whole chain. The characteristics of the sludge may change over the FSM chain, for example, water might be removed from sludge during a pre-treatment stage;

(ii) Data relating to the economics of the FSM chain: costs and revenues at the different stages.

Table 5.1 broadly summarises the key inputs and output parameters that are required for each module and Appendix 9 gives the datasets used for eThekwini and Dakar for this work.

Table 5.1: Summary of input and output parameters for each module of the model

Module number	Module	Input parameters	Output parameters	Key control parameters (where applicable)
1	Pit conditions & environment / Sludge characteristics	Population data Geographical conditions Usage data Sludge accumulation and degradation rates	Key property characteristics of sludge present in pits (e.g. water content, calorific value) – inputted measured values or estimated by model from other inputs	
2	Pit emptying	Chosen emptying method Capital, labour and consumables costs Revenue generated Any additions that change sludge characteristics (e.g. water)	Properties of sludge sent to transfer Costs and revenue associated with emptying	
3	Sludge conveyance	Chosen conveyance method (e.g. handcart, tanker) Geographical conditions Capital, labour and consumables costs Feed properties Any changes to sludge characteristics during transport	Properties of sludge sent to storage Costs/revenue associated with conveyance	Allowable combinations of emptying and conveyance methods
4	Sludge storage for LaDePa	Capital, labour and consumables costs Feed properties Storage time required	Properties of sludge sent to pre-treatment Costs/revenue associated with storage	Key properties of sludge going to treatment: flowrate, water content, calorific value, nutrient content
5	LaDePa pre-treatment	Capital, labour and consumables costs Feed properties Feed specification for LaDePa LaDePa volumetric capacity	Output sludge stream properties Costs	Comparison of pre-treated sludge against LaDepa feed specification
6	LaDePa process	Capital, labour and consumables costs Feed properties	Output product properties Costs	Minimum spec of feed required for treatment (flow, water content, calorific value)
7	Sale / disposal of LaDePa pellets	Product properties Options for sale/disposal Additional costs for each sale/disposal method	Costs & revenues	
8	Sale / disposal of LaDePa by-products	By-product properties Options for disposal Costs/revenues	Costs	

Module number	Module	Input parameters	Output parameters	Key control parameters (where applicable)
9	LaDePa cash flows and NPV calculation	Costs and revenues from all previous modules	Levelised cost per pit, per tonne of dry solids and per tonne of pellet product	
11	Storage for Combustion	Flows and properties of incoming sludge Storage time required Costs	Flow and properties of sludge to pre-treatment	
12	Combustion pre-treatment	Capital, labour and consumables costs Feed properties Pre-treatment output requirements	Output sludge stream properties Costs	Comparison of pre-treated sludge properties against feed specification for combustion.
13	Combustion process	Capital, labour and consumables costs Feed properties	Output ash product properties Costs	Minimum spec of feed required for treatment (flow, water content, calorific value)
14	Sale / disposal of ash	Ash properties Options for sale/disposal Costs / revenues for each option	Costs & revenues	
15	Sale / disposal of combustion by-products	Detritus and off-gas properties and flows Options for disposal Costs/revenues	Costs	
16	Combustion cash flows and NPV calculation	Costs and revenues from all previous modules relevant to combustion	Levelised cost per pit, per tonne of dry solids and per dry tonne of ash	
17	Landfill costs and cash flows	Sludge flow and properties to be sent to landfill Landfill charges	Levelised cost per pit and per tonne of dry solids	
18	Service provider costs	Percentage fee	Overall costs of service provision for all three methods	
19	Product valuation	Nutrient content of pellets and ash Prices for commercial inorganic and organic fertilisers	Sludge product values based on inorganic and organic fertiliser prices	
20	Crop application	Chosen crop nutrient demand Chosen inorganic and organic fertiliser nutrient contents Transport and fertiliser spreading costs	Maximum selling price for LaDePa pellets to be able to compete with commercially available fertilisers	

5.1 eThekwini municipality, South Africa

The full data set of input parameters for the eThekwini context is given in Appendix 9. This section provides a summary of the background to the eThekwini context and the key pieces of input data.

5.1.1 Background to FSM in eThekwini

A pit-emptying programme was implemented by EWS from 2007 to 2010 in order to empty in the region of 35 000 pits throughout the municipality containing sludge from the previous 10 to 20 years. The age of the sludge was on average 14 years. Since this time, the FSM structure has changed and pits emptied during future cycles should only contain sludge from the previous 5 years as a maximum. This sanitation service is financed by the municipality with households being offered one free pit-emptying service every 5 years. Any additional services will be at the householder's expense.

The pits currently being serviced by the pit-emptying programme are all VIP toilets, the majority of which are relatively dry, containing sludge that cannot be pumped. As a result, manual emptying of these VIPs takes place. There is generally sufficient access to allow a pick-up truck near enough to a house such that a container of sludge can be transferred from the pit-side to the back of the truck without intermediate transport.

During the previous pit emptying cycle it became clear that EWS needed to identify suitable methods of disposal. Disposal to a wastewater treatment works was unsuccessful and led to nitrification problems and organic overloading, and on-site burial was not possible in dense areas. Future pit-emptying cycles will only add to this burden. These challenges led to EWS seeking innovative solutions, and resulted in the development of the LaDePa pelletiser together with PSS.

The business model that was then developed for FSM within eThekwini is as follows:

- EWS appoints a managing contractor.
- The managing contractor appoints independent pit-emptying sub-contractors to empty pits, paid on the basis of the volume of sludge delivered to the LaDePa machine;
- The managing contractor manages both the pit-emptying sub-contractors and the sludge processing through the LaDePa plant.
- EWS retains ownership of the pelletised product and arranges its sale and / or end use.

The municipality plans to deploy four LaDePa plants across the municipality during the next pit-emptying cycle, based at existing wastewater treatment plants to ensure ease of access.

5.1.2 Pit conditions and sludge composition

The properties of sludge from eThekwini VIP toilets have been studied in detail in a related project (Mechanical Properties of Faecal Sludge; contract # 21268) and data was taken from this work to provide average values for the expected sludge composition from pits in eThekwini. A summary of the data used in the model is provided in Table 5.2. The full data set from which these figures were taken is provided in the Phase 3 report (Appendix 3) and in Appendix 11 which provides the details of all the analyses carried out during the course of this project.

Table 5.2: Summary of VIP sludge analysis (Zuma et al. 2013)

Parameter	Unit	Range of results	
		VIP (wet); n = 10	VIP (dry); n = 10
Water content	%	40 - 91	65 - 89
Chemical Oxygen Demand (COD)	g COD / g wet mass	35 - 207	17 - 224
Volatile solids (VS)	g VS / g dry mass	0.24 - 0.9	0.24 - 0.82
Total Kjeldahl Nitrogen (TKN) (organic N + ammonia-N + ammonium-N)	g TKN / g wet mass	2 - 15	3 - 97
Ammonia	g NH_3 / g wet mass	0 - 0.0048	0 - 0.058
pH		4.6 - 8.6	4.7 - 8.7
Ortho-phosphate	mg / g wet mass	0.2 - 1.7	0.1 - 1.7
Thermal conductivity	W / m K	0.47 - 0.72	0.42 - 0.59
Calorific value	kJ / kg dry mass	2 869 - 21, 104	2 869 - 23,870
Density	kg / m^3	745 – 2 606	

The water content of the sludge in pits is dependent on environmental conditions. Wetter pits do exist in eThekwini, predominantly in areas with high groundwater. The majority of pits are however dry, and therefore data from these pits were used as more representative average values for inputs to the model.

It was not possible to obtain data for total nitrogen or potassium in the raw sludge due to a lack of the necessary equipment at the time.

5.1.3 LaDePa operational data

The LaDePa plant was unfortunately not operational during the course of this project due to a breakdown and delays in obtaining approval for repairs to be undertaken. This resulted in an inability to confirm the optimum operational parameters for the LaDePa such as feed sludge water content, belt speed, MIR power etc. In addition, it was planned to obtain a sample of the sludge prior to processing for analysis followed by an analysis of the resulting pellets in order to compare input and output characteristics. This was therefore not possible, and the sludge data was taken from previous analyses of pit sludge and the pellets were samples produced from stock piled sludge (and therefore no knowledge of the source and age of the sludge, or the age of the pellets).

Delivery of the pilot-scale LaDePa machine which was to be used to undertake experimental trials was also delayed and only arrived in the Pollution Research Group's laboratory in early September 2013. This did not allow for sufficient time for any research work to be undertaken for the final model.

During the course of the next 6 months it is envisaged that trials will be undertaken on the pilot scale machine in order to identify optimum operational conditions (under a WRC project: k5/2137 -

Characterisation of on-site sanitation material and products: VIP latrines and pour flush toilets), and the full-scale plant should also be operational. As such, the data on the operation of the machine, the sludge characteristics and "fresh" pellets would then become available. Table 5.3 summarises the operating and financial data relating to the LaDePa process that was used in the model. Data was obtained from EWS' previous experience in operating the plant and PSS manufacturer's data on the eThekwini plant.

Table 5.3 Summary of financial and operational data for the LaDePa process

	Value	Unit	Reference	Comment
Financial parameters				
Plant lease rate	60 000	USD / year	EWS	Guide - not the finalised rate.
Plant royalties rate	50 000	USD / year	EWS	Guide - not the finalised rate.
Permitting & health and safety costs	2 000	USD / year	Estimate	Annual permit fees etc.
Personnel costs				
Foreman	1 000	USD / month	Typical rate for South Africa	One per plant
Labourers	13.5	USD / day	Typical rate for South Africa	The next pit-emptying cycle will include 4 labourers for plant operation
Project manager	3 500	USD / month	Typical rate for South Africa	Part-time only
Miscellaneous consumables	500	USD / month	EWS	
Environmental impact assessment for LaDePa plant	12 700	USD / assessment	EWS	Underway, in early stages.
Cost of sludge or detritus disposal to sanitary landfill	170	USD / tonne	EWS	From wastewater treatment works to final disposal at landfill site (includes transport).
Operational parameters				
LaDePa volumetric capacity	6	m^3 / day	EWS	Estimate: feed flow is not measured. Controlled by sight (aim to maintain screw feeder full of sludge for smooth operation)
Feed dry solids content	30	%	EWS	Estimate – not measured.
Product dry solids content	85.5	%	PRG 2013	Average from 3 samples of pellets analysed.
Power demand of LaDePa	152	kW	PSS data sheet	Current EWS plant – multiple sizes of plant available from PSS. Generator is oversized for current plant (310 kW (PSS 2013)).
LaDePa process variables	Screw speed; belt speed; MIR power		EWS	Screw separates detritus from sludge, belt carries pellets through the process. Increasing MIR power increases the load on the generator and produces more heat in the exhaust gases used for the pre-drying stage of the process.
Residence time of sludge in LaDePa plant	8	mins	PSS data sheet	Includes pre-drying and MIR
LaDePa operating days	22	Days / month	EWS	
LaDePa operating hours	9	Hours / day		
Proposed contractual downtime (max allowed per month)	25	% of working days	EWS	
Proposed contractual downtime (max allowed per year)	5 – 10	% of working days	EWS	
Plant lifetime	10	years	Estimate	Different parts of the plant have significantly different lifespans.

5.1.4 Combustion financial and operating data

The combustion section of the model was originally to be based on a local fluidised bed incinerator at the KwaMashu wastewater treatment works (KwaZulu-Natal, South Africa). Unfortunately the operator of the plant was unwilling to release operational and financial data on the plant. Therefore the majority of the parameters relating to the incineration plant have been taken from literature. There was limited data available on combustion plants of the size being considered for this application, particularly for the South African context. Table 5.4 provides a summary of the key financial and operating parameters used in the model.

Table 5.4: Summary of key financial and operating data for the fluidised bed incineration process

	Value	Unit	Reference	Comment
Financial parameters				
Capital cost of plant	7 300 000	USD	Scaled from figures in Toronto Water 2011 & Ontario Ministry of Environment 2009	
Waste licence	10 000	USD	Estimate	Based on current waste license costs for other applications
Atmospheric emission license	5 000	USD	Estimate	
Personnel costs				
Foreman	1 000	USD / month	Typical rate for South Africa	Two per plant
Labourers	700	USD / month	Typical rate for South Africa	16 per plant at KwaMashu WWTP.
Project manager	3 500	USD / month	Typical rate for South Africa	Part-time only
Cost of ash disposal to general landfill	130	USD / tonne	Estimate	Estimate from current cost of hazardous landfill
Operational parameters				
Plant capacity	400	dry kg/hour feed	Coal & Waste Utilisation	KwaMashu conditions
Operating hours per day	24	Working hours/day	Coal & Waste Utilisation	KwaMashu conditions
Operating months per year	12	months/year	Coal & Waste Utilisation	KwaMashu conditions
Temperature of furnace	760 - 815	˚C	Dangtran et al. 2000	
Excess air requirement	40	%	Dangtran et al. 2000	
Plant lifetime	20	years	Estimate	
Mass reduction across combustion process	70	%	Lauridsen 2008	
Volume reduction across combustion process	90	%	Lauridsen 2008	
Average downtime per year	10	%	Estimate	

Some preliminary tests were carried out on the wastewater sludge feed to the incinerator. It was envisaged that these results would be used in the model, to calculate the change in sludge composition across the incineration process. However, due to the lack of a full data set, particularly the total N and total K values for the wastewater sludge, this did not take place.

5.1.5 Sale and use of sludge endproducts

Re-use of treated sludge in agriculture is regulated by the Department of Agriculture, Forestry and Fisheries (DAFF). The 2012 Fertiliser Regulations (DAFF 2012) provide limits on the levels of various components permitted in sludge endproducts to be used in agriculture. New fertiliser products must be registered with the DAFF. The total cost of the registration process, including the fertiliser analysis requirements, is estimated as 650 USD per product (Pers.com. A Mostert (Fertiliser Society of South Africa), June 2013).

5.2 Dakar, Senegal

In order to determine if the spread sheet model was applicable to scenarios other than the eThekwini Municipality, data from West Africa (Dakar, Senegal) was obtained through SANDEC, a project partner. SANDEC collated data on the characteristics of faecal sludge in Dakar and the composition and cost of fertiliser from existing literature and personal interviews. The Phase 4 report (Appendix 5) includes a detailed report on the data gathering process. Appendix 9 gives the full Dakar data set used in the model. This section provides a brief background to the Dakar context and a summary of the key input data.

Sludge processing through LaDePa or combustion does not occur in Dakar, therefore local input data were not available for these stages of the model.

5.2.1 Background

The majority of sanitation in Dakar is provided by onsite sanitation systems, predominantly septic tanks. Sludge is removed either manually or mechanically using vacuum tankers. Reported time frames for de-sludging range from more than twice a year to once every two years. It is estimated that while 1,500 m3/day of faecal sludge is delivered to treatment plants, an additional 4 500 m3/day of collected faecal sludge are disposed of into the environment. This therefore highlights the need to investigate other methods for the processing and disposal of sludge and ways of incentivising safe disposal.

Septic tank emptying is carried out by private operators. While approximately 130 emptying trucks operate in the Dakar area, only 20% are solely in the business of FS sanitation service (Mbéguéré et al., 2012). On average each company has one truck, and there are approximately ten formal companies. After septic tanks are emptied, the vacuum trucks carry the sludge to the three FSTPs where sludge is first dewatered in settling/thickening tanks. The thickened sludge (after one week of settling) is then pumped to unplanted drying beds. Leachate from drying beds and supernatants from settling/thickening tanks are in turn processed at the co-existing WWTPs. There are currently 3 FSTPs which were established from 2006 by ONAS (a government body) under the Water Long Term Program.

5.2.2 Sludge properties

A summary of the typical properties of sludge removed from septic tanks in Dakar is given in Table 5.5. These figures were used as inputs to the model. Sludge is generally far wetter than that of typical VIP pit sludge from eThekwini, and this impacts on the emptying and conveyance methods that can be used, and the level of pre-treatment required.

Table 5.5: Typical properties of faecal sludge in Dakar, Senegal

Parameter	Value	Units	Reference
Average dry solids content of sludge in pits	0.62	%DS	Nekam 2010
Detritus content	3	%vol	Dème, 2007
Sand content	0.87	%vol	Estimated from Dème, 2007
Average calorific value	17	MJ/kg	Dione 2012
Average density	1 000	kg/m^3	Estimate, based on very high water content
Total nitrogen	78	mg N / g DS	TKN range: 34 - 121 mg TKN / g DS from Walker 2007, Sonko 2008 and Badji 2008. Choose value of 78 mg N / g DS (although TKN < TN)
Total phosphate	0.1	mg P / g DS	Badji 2008 0.04 mg P / g DS, El Hadji (unpublished) 0.07 - 0.13 mg P / g DS
Potassium	0.76	mg K / g DS	Nekam 2010 - average of 3 composite samples
Ascaris – undeveloped eggs	39.33	No. possible viable Ascaris / 20g DS	Sonko 2007 - number of viable helminth ova

5.2.3 Sale and use of sludge endproducts

The combination of phosphoric acid with ammonia and potash is used to produce NPK fertilizers which are manufactured by ICS (Industrie Chimique du Sénégal). The official prices have been standardized by the Government after discussion with the suppliers. The market for organic fertilisers is also increasing and farmers make use of animal faeces, plant compost, faecal sludge and wastewater sludge to improve the growth of their crops.

In 2010 the Economic Community of West Africa states (ECOWAS) and UEMOA Commissions embarked on the development of a regional legal framework that would harmonise national regulatory schemes governing fertilizer quality control. However, it has not yet been published or adopted by the member states. Therefore currently there is no registration process or regulation of sludge fertiliser products in Dakar.

6 Model validation and sensitivity analysis

6.1 Model validation

Validation of the model was carried out in two ways:

(i) Entering a set of input data for a particular context and checking the output calculated costs for specific services against the known current prices for those services or literature values;

(ii) Review of the model inputs, structure and outputs with an experienced sanitation service provider.

6.1.1 Validation data

Table 6.1 compares the model outputs against the actual costs (based on service providers' charges and literature data) and operational parameters. Table 6.2 provides detailed notes on each of the validation comparisons. All costs are 2013 prices, scaled with inflation at 6%, converted using 10 ZAR – USD (Rand – South Africa) and 495 FCFA – USD (CFA Franc - Senegal) exchange rates (applicable at 30 September 2013).

Table 6.1 Validation summary table

	Actual price	Model output	Units
eThekwini municipality, South Africa			
Price charged for pit-emptying by pit emptying sub-contractors	173	158	USD/pit
Number of pits emptied per day	2	2.05	No./day
Overall cost of pit-emptying programme	248	211	USD/pit
Combustion operating costs	107	184	USD/tonne
Dakar, Senegal			
Price charged by pit-emptying companies	64	75	USD/pit
Number of pits emptied per day	4	6.06	No./day

Table 6.2: Detailed notes on each of the validation comparisons in Table 6.1

eThekwini municipality			
Price charged for pit-emptying by pit emptying sub-contractors [173 USD/pit actual; 158 USD/pit model output]			
eThekwini municipality 2009 – 2010 pit-emptying cycle	173	USD / pit	Salisbury & Still 2011 Includes medical costs, bulk purchases & equipment hire. ZAR 1,727 / pit (2010 cost scaled to 2013 prices). 31,000 pit latrines were emptied over this pit-emptying cycle.
Model output	158	USD / pit	Key inputs: Number of pits 35,000 pits over a 5 year pit emptying cycle, sludge accumulation rate in pit of 40 ℓ/person/year, average 5 persons/household, 30%DS in sludge, average distance 12 km from pit to sludge disposal site, average distance 15 km from pit-emptying sub-contractor's base to pit, sub-contractor mark-up rate 30%, specified 2 pits emptied / day / team
Number of pits emptied per day [2 actual; 2.05 model output]			
eThekwini municipality 2009 – 2010 pit-emptying cycle	2	Pits / day	Pers. comm. D Wilson & J Harrison (eThekwini Water & Sanitation) 2013, for manual emptying and transport of sludge to LaDePa site with pick-up trucks.
Model output	2.05	Calculated number of pits possible to empty / day	For the manual emptying and sludge conveyance with pick-up trucks. Calculated based on the inputs entered for emptying rates, times for set-up and clean-up, travel distances and speeds (Note: an optional input enables the user to override this calculated figure in the model and input a set figure for the number of pits emptied per day).
Overall cost of pit-emptying programme [248 USD/pit actual; 211 USD/pit model output]			
eThekwini municipality 2009 – 2010 pit-emptying cycle	248	USD / pit	Salisbury & Still 2011 Average cost per pit 2,084 USD at 2010 prices. Included sub-contractor fees for pit-emptying, managing contractor costs, site establishment, equipment and project manager costs. Landfill costs were excluded from this cost as they were very low per pit, because a large quantity of sludge was buried on site. Cost includes some processing / disposal of sludge off-site, but amount unknown.
Model output for pit emptying and managing contractor costs only	211	USD / pit	Cost of pit-emptying and managing contractor costs. LaDePa, combustion and landfill costs excluded. Managing contractor costs calculated as ZAR 533 / pit.
Combustion operating costs [107 USD/tonne actual; 184 USD/tonne model output]			
Operating costs for waste incineration - from literature	107	USD / tonne	Greater London Authority 2008. 50 GBP/tonne (assumed wet tonne) waste given as 2008 operating costs for incineration for a 100 – 115 kte/year plant (the smallest considered in the report). Operating costs decrease as size of plant increases.
Model output	184	USD / tonne	613 USD / dry tonne at 30%DS gives 184 USD / wet tonne feed (excluding costs of pit-emptying and conveyance). Plant size assumed in model: 3.14 dry kte/year or 10.5 wet kte/year. Cost therefore likely to be higher than the literature cost given above, due to economies of scale. The UK cost would also have to be scaled to be applicable in South Africa.

Dakar, Senegal			
Price charged by pit-emptying companies [64 USD/pit actual; 45 USD/pit model output]			
Price quoted by local pit-emptying contractors	64	USD / pit	Gning 2009 - 25,000 FCFA given as the 2009 price, 31,562 FCFA scaled to 2013 costs.
Model output	45	USD / pit	Key inputs: Sludge accumulation rate in pit of 985.5 ℓ/person/year (2.7 L/capital/d), average 10 persons/household, 0.62%DS in sludge (majority septic tanks), average distance 12 km from pit to sludge disposal site, average distance 7 km from pit-emptying sub-contractor's base to pit, sub-contractor mark-up rate 35%, specified 4 pits emptied / day / team
Number of pits emptied per day [4 actual; 3.18 model output]			
Literature	4	Pits / day	Gning 2009 – average number of trips made by tankers per day to discharge at faecal sludge treatment plant
Model output	3.18	Pits / day	For emptying and conveyance with large vacuum tankers. Calculated based on the inputs entered for emptying rates, times for set-up and clean-up, travel distances and speeds (Note: an optional input enables the user to override this calculated figure in the model and input a set figure for the number of pits emptied per day).

The majority of the calculated model outputs agree well with the known values for these parameters. A better validation could be performed using the eThekwini data compared to the Dakar data as it was possible to have detailed discussions with the sanitation service provider (eThekwini Water and Sanitation - EWS) about a previous, large-scale organised pit-emptying programme where financial records existed. Although pit-emptying and sludge treatment takes place on a large-scale in Dakar, the data available for comparison with the model were mainly discrete values taken from the literature. Operational complexities affecting the economics of the Dakar system were not necessarily as apparent as in the eThekwini case.

Examples of details in the model that were modified or confirmed during validation of the model with EWS include:

- During the eThekwini pit-emptying cycle, each manual pit-emptying team was preceded by an advance team which ensured that the emptying team would be able to access the pit the next day to empty it, e.g. by opening access routes and removing parts of the toilet superstructure where necessary. The ‘access level’ factors included in the model – which allow for extra time to gain access to empty the pit – therefore remained low, but an extra two people per team were required in addition to the four team members removing sludge from the pits;
- The number of pits that were emptied per day, on average, during the previous pit-emptying cycle was set at 2;
- The average detritus content in the sludge removed from pits was estimated as 20%, with the likelihood being that this will have decreased by the next pit-emptying cycle;
- In eThekwini, detritus was only removed from sludge at the LaDePa plant, not in a dedicated pre-treatment stage. This impacts on the number of LaDePa plants required, as they operate based on a volumetric feed capacity;
- Possible locations of future LaDePa plants are known, and distance inputs to the model could therefore be more accurately predicted.

6.1.2 Comments on the validation results

The model outputs agree well with the actual prices charged for pit-emptying in eThekwini, and for the number of pits emptied per day for the eThekwini and Dakar cases. This tested the model for both manual emptying and large vacuum tanker emptying methods. The calculated price charged per pit in Dakar was somewhat lower than the literature value for pit-emptying fee, however the mark-up rate used in the model was an estimate. It should be noted that these costs and numbers are sensitive to distances travelled, sludge accumulation rates and the dry solids content of the sludge being removed, all of which are discussed in further detail in Section 8.

The overall cost of pit-emptying predicted by the model, including the managing contractor’s costs but excluding sludge-processing costs (LaDePa and combustion), was slightly lower than the costs for eThekwini’s previous round of pit-emptying. This is partly due to higher R&D costs in the previous round than would normally be expected, and partly because the first round costs made allowances for an unknown portion of sludge being disposed of off-site (the majority was buried on-site). Therefore costs for the previous round included an unknown value for sludge transport and disposal costs, which are not included in the figure taken from the model for validation.

The LaDePa operating costs could not be directly validated against existing financial figures (these figures are not currently available). The inputs, model structure and results were however reviewed with EWS for accuracy.

The combustion operating cost calculated by the model is significantly higher than the cost given in the literature. This is principally due to differences in the sizes of plant being considered, and the economies of scale that exist with larger plants. Literature values for small incineration plants (under 25 kt/year feed) could not be found for the validation. The original intention was to obtain data from a local incinerator processing sewage sludge, but the company was unwilling to share operational and financial data. Further work is required to review detailed information on small incinerators. This is discussed further in Section 10.

6.2 Sensitivity analysis

The purpose of the sensitivity analysis is to identify those input parameters where a small change in the value has a large impact on the model outputs. These inputs are important to take note of when running the model for the following reasons:

(i) The accuracy of the values assigned to these inputs is consequently more important than for other input values;
(ii) The expected range in the model outputs can be checked by varying these input values.

6.2.1 Sensitivity analysis methodology

As it was not practicable to check the model's response to the variation of every input parameter, the inputs to be analysed were selected as follows:

- High value financial inputs (e.g. capital costs of large machinery);
- Inputs with a significant impact on operational efficiency (e.g. transport distances);
- Input parameters where an accurate value for the parameter was difficult to set (e.g. the applicable site establishment fees for the managing contractor);
- Inputs known to be correlated to other inputs, but where the correlation was not accounted for by the model and the strength of correlation unknown (e.g. the relationship between the dry solids content of sludge and the sludge accumulation rate in a pit).

A sensitivity analysis was carried out on the factors affecting the costs of sludge disposal, setting the sale price of sludge products to zero. The results are discussed in this section. A second sensitivity analysis was carried out on inputs that affected the possible value of the sludge products, these results are discussed under Section 7 – Product valuation.

Table 6.3 lists the input parameters that were analysed, the output parameters that were monitored, and the values for these applicable to the base case scenario for the sensitivity analysis.

The model was run using the manual emptying option, with conveyance of sludge in containers on pick-up trucks. LaDePa, combustion and landfill processing/disposal options were considered. Sale price of products (LaDePa pellets and combustion ash) were set to 0 to allow sensitivity of costs only to be analysed.

Table 6.3 Parameters included in the sensitivity analysis of the model

Ref. no.[1]	Variable	Value	Unit	Notes
	Inputs - general			
1	Number of pits emptied per pit-emptying cycle	35 000	No. / cycle	
2, 4a	Length of pit-emptying cycle	5	years / cycle	
	Number of years between pit-emptying cycles	0	years	
4b, 4c	Frequency of pit-emptying	5	years	
	Number of people using each pit	5	No. / pit	
12	Sludge dry solids content	30	%DS	
5	Sludge detritus content	20	%vol	
3, 13	Sludge accumulation rate	40	ℓ / person / year	
6	Wet sludge density	1 150	kg / m^3	
	Proportion of total pit contents removed	95	%	
7	Distance from pit to LaDePa or combustion plant site (distance T1)	12	km	
8	Distance from pit-emptying subcontractor's base to pit emptying site (distance E1)	15	km	
	Capital cost of pick-up truck	17 500	USD	
9	Pit-emptying subcontractor mark-up	30	%	
	Managing contractor establishment costs	100 000	USD	
	Managing contractor monthly costs	5 000	USD / month	
10	Managing contractor mark-up rate	15	%	
11	Total cost lease and royalties for LaDePa	110 000	USD / year	
14	Minimum dry solids in feed sludge to LaDePa	20	%DS	
15	Volumetric feed rate to LaDePa	6	m^3 / day / plant	
16	LaDePa pellet average dry solids content	85.5	%DS	
17	Minimum dry solids in feed to combustion	20	%DS	
18	Calorific value of sludge feed to combustion	12.35	MJ / kg dry solids	
19	Capital cost of combustion plant	7 300 000	USD	
20	Escalation rate on costs and revenues, excluding fuel	6	%	
21	Escalation rate on fuel	12	%	
22	Discount rate	8	%	
23	Interest rate on debt	9	%	
	Diesel price	1.234	USD / ℓ	
24	Cost of disposal to hazardous landfill (raw sludge or detritus from LaDePa)	170	USD / tonne	
	Product sale price	0	USD / tonne	Set to 0 to look at sensitivity of costs only

Ref. no.[1]	Variable	Value	Unit	Notes
	Outputs			
	Levelised[2] cost of pit-emptying and conveyance only	158	USD / pit	
	Levelised cost of pit-emptying, conveyance and processing through LaDePa, per pit	376	USD / pit	Excluding revenues
	Levelised cost of pit-emptying, conveyance and processing through combustion, per pit	338	USD / pit	Excluding revenues
	Levelised cost of pit-emptying, conveyance and disposal to hazardous landfill	326	USD / pit	
	Levelised cost of producing one tonne of LaDePa pellets	1 227	USD / tonne	Excluding revenues
	Levelised cost of producing one dry tonne of combustion ash	2 279	USD / dry tonne	Excluding revenues
	Number of LaDePa plants required	5	No. plants	4.66 plants' capacity required
	Number of combustion plants required	1	No. plants	0.63 plant capacity required
	Nutrient value of LaDePa pellets based on inorganic fertiliser prices	48	USD / tonne	
	Maximum sale price for LaDePa pellets to be cost-equal with commercial organic fertiliser.	18	USD / tonne	Negative figure indicates LaDePa pellets are always more expensive to apply under the conditions selected

[1] Reference numbers appear where a sensitivity analysis case was run for the variable. Other variables are included for information on the base case.
[2] 'Levelised' cost refers to the sum of the discounted net costs divided by the sum of pits emptied or tonnes of product made over the chosen cash flow period.

One input parameter was chosen at a time as the independent variable and the model run for a range of input values for that parameter. Values of the following dependent variables (outputs) were recorded:

- Total cost per pit for the LaDePa process;
- Total cost per pit for combustion;
- Total cost per pit with sludge disposal to hazardous landfill.

To compare the relative sensitivities of model outputs to different model inputs, a normalised sensitivity index, SI_N, was calculated for each input parameter. The following method was used:

A sensitivity index, SI_D, was calculated for each dependent variable using the method described by Hamby (1994). This is the relative change in output with a change in an input, maintaining other inputs at their base case values:

$$SI_D = \frac{D_{max} - D_{min}}{D_{max}}$$

Where:
D_{max} = maximum value of the dependent variable
D_{min} = minimum value of the dependent variable

The magnitude of the sensitivity index provides a measure of the impact of the independent variable on the model outputs. For a given independent variable, the SI_D values of the costs for the three disposal methods can be compared to determine which method is most sensitive to changes in the independent variable being considered.

The sensitivity index value for the independent variable, SI_I, was similarly calculated as follows:

$$SI_I = \frac{I_{max} - I_{min}}{I_{max}}$$

Where

I_{max}= maximum value chosen for the independent variable
I_{min}= minimum value chosen for the independent variable

An appropriate range of values was chosen for the sensitivity analysis for each independent variable. As a consequence, the SI_I for each independent variable was different. To enable comparison between SI_D values for disposal costs for different independent variables, the change in SI_D with incremental change in SI_I was required. This was found by calculating the normalised SI value, SI_N, as follows:

$$SI_N = \frac{SI_D}{SI_I}$$

This allowed, for example, the sensitivity of the cost of LaDePa disposal to changes in sludge dry solids to be compared to the sensitivity of LaDePa cost to changes in detritus content of the sludge, and thus an indication given of the relative impact of the two variables on the outputs of the model.

As an example, assume that it costs 1 USD/km to own, operate and maintain a 2 tonne truck. Assume that fuel costs 1 USD per litre, and that fuel comes to 25 cents/km in the cost calculations. The sensitivity of the vehicle operating cost to fluctuations in the fuel price would be analysed as follows:

i) Vary the fuel price from 50 cents/litre (i.e. half) to 2 USD per litre (i.e. double)
ii) With this range in fuel price the cost of fuel per km will range from 12.5 cents to 50 cents
iii) The total cost to own and operate the vehicle will then range from 87.5 cents/km to 1.25 USD per litre
iv) If the price of fuel is taken as the independent variable, and the vehicle cost per km is taken as the dependent variable, then

$$SI_D = \frac{1.25 - 0.875}{1.25} = 0.30$$

$$SI_I = \frac{2.0 - 0.50}{2.0} = 0.75$$

and

$$SI_N = \frac{0.30}{0.75} = 0.40$$

An SI_N of 0 would imply that there is no relationship at all between the input and the output parameters, whereas an SI_N of 1.0 implies that there is the same proportional change in both parameters across the span of the input ranges investigated. SI_N can be greater than 1.0, which would be the case if a small change in the independent variable (say a 50% increase) produced a large change in the dependent variable (say a 200% increase – for these changes the SI_N would be equal to 2.0).

The sensitivity indices provide only a measure of the relative input that an input variable has on the model outputs. They do not describe the nature of the correlation between the input and outputs.

The normalised SI values calculated will only be applicable across the range of values chosen for the independent variable, and for the base case values chosen. The rate of change of the dependent variable is not always constant, therefore the SI_N value does not serve to predict particular values of the dependent variable within the range of independent variable values under consideration. The SI_N values can be used to provide a comparison of the relative level of impact of different input variables on the outputs of the model, for the range of input values that could be expected in a real-life context.

Although the calculated values for sensitivity indices are associated with a particular set of model input values, the inputs that arise as significant from one model case will provide guidance as to inputs of possible importance for other model cases run. As the model is run with a greater number of different sets of input data, a better picture will be built up of the inputs that are generally most significant to the outputs of the model. For further detail on the relationships between model inputs and outputs, see Section 8 of this report.

6.2.2 Sensitivity of sludge disposal costs to model inputs

Chart 6.1 shows the normalised sensitivity index values for the three disposal routes, for all the independent variables considered that related to the cost (only) of sludge disposal. Note that not all independent variables are applicable to disposal routes (e.g. the LaDePa lease and royalties rate clearly only applies to the LaDePa disposal route). Chart 6.2, Chart 6.3 and Chart 6.4 show the SI_N values applicable to each disposal method, sorted in ascending order. Data tables, including notes on the conditions for which each sensitivity case was run, are given in Appendix 10. The reference numbers from Table 6.3 are shown next to each entry on the x-axes of the charts.

The following model inputs have the most significant impact on the costs of disposal for all three disposal methods, with SI_N values over 0.4:

- Length of the pit emptying cycle – the time taken to empty all pits, with a variable pit-emptying frequency;
- Length of the pit-emptying cycle, with a fixed pit-emptying frequency of 5 years;
- Sludge accumulation rate in pits, whilst maintaining a constant total mass of dry solids in the pit (i.e. sludge dry solids content varies in proportion to sludge volume in the pit);
- Sludge accumulation rate, with a fixed dry solids concentration in the sludge (and therefore a variable total mass of solids in the pit);
- The discount rate used in the cash flow analyses.

In addition, the following inputs had the most significant impact on the cost of processing sludge via the following specific routes (SI_N values over 0.4 for the applicable disposal route):

LaDePa:

- The sludge dry solids content in the pit;
- The minimum dry solids content required in the LaDePa feed;
- The volumetric feed capacity of the LaDePa plant;

Combustion:

- The number of pits emptied per cycle;
- The wet sludge density;
- The sludge dry solids content in the pit;
- The capital cost of the combustion plant;
- The escalation rate on costs and revenues, excluding fuel

Landfill:

- The wet sludge density;
- The cost of hazardous landfill.

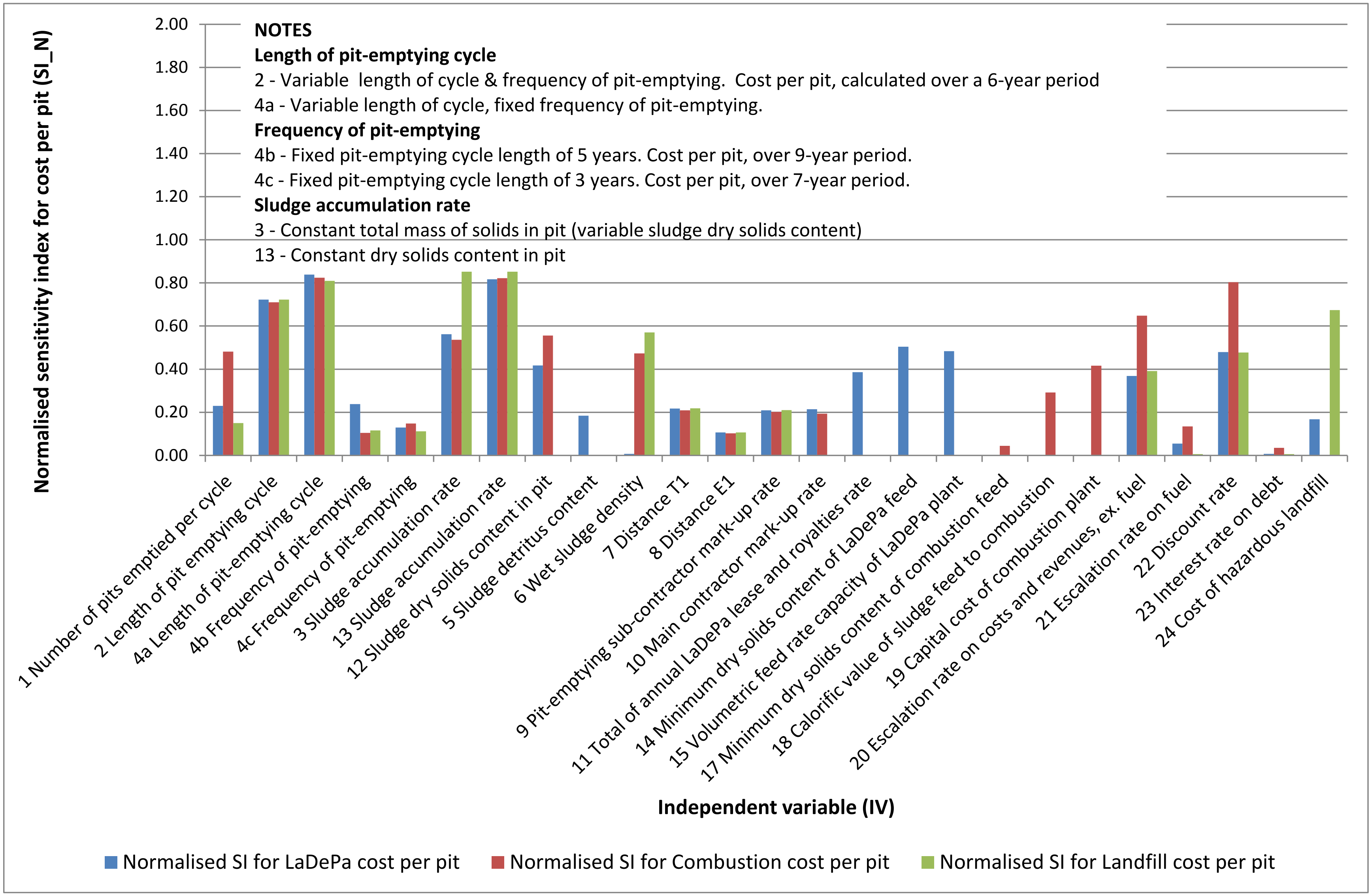

Chart 6.1: Normalised sensitivity index values for the three disposal routes

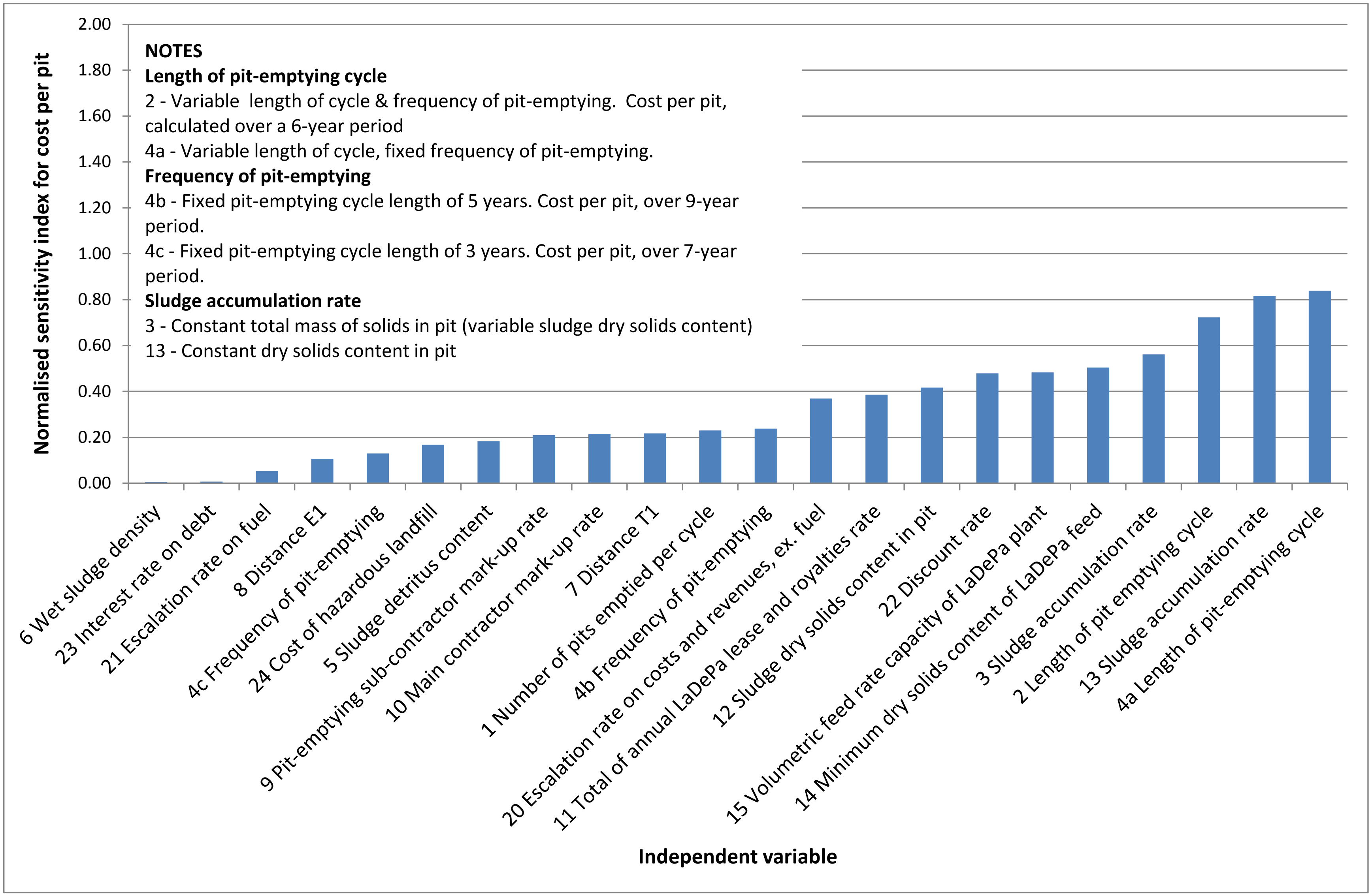

Chart 6.2: Normalised senstivity indexvalues for the cost per pit for the LaDePa process, sorted in ascending order

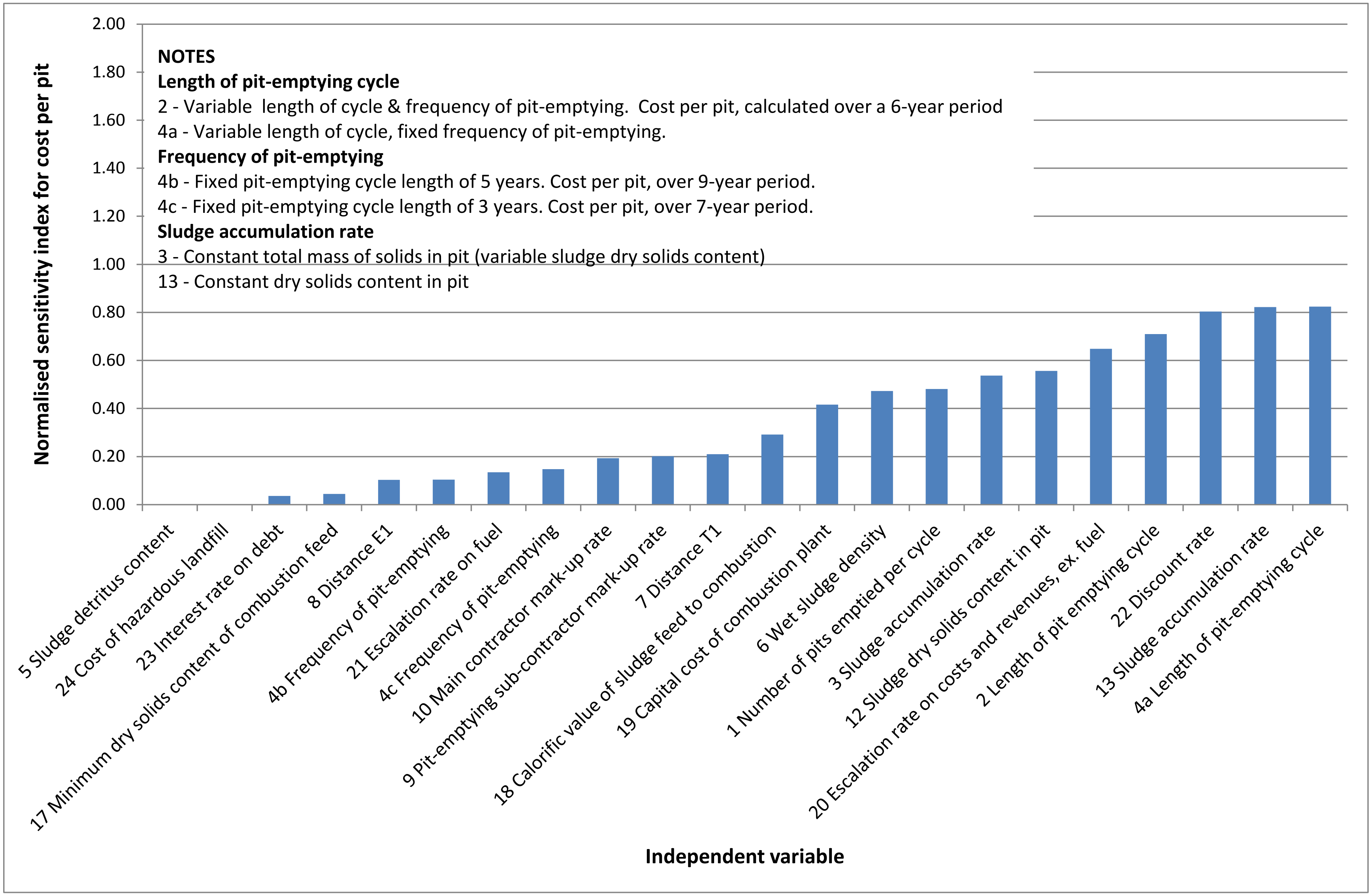

Chart 6.3: Normalised sensitivity index values for the cost per pit for combustion, sorted in ascending order

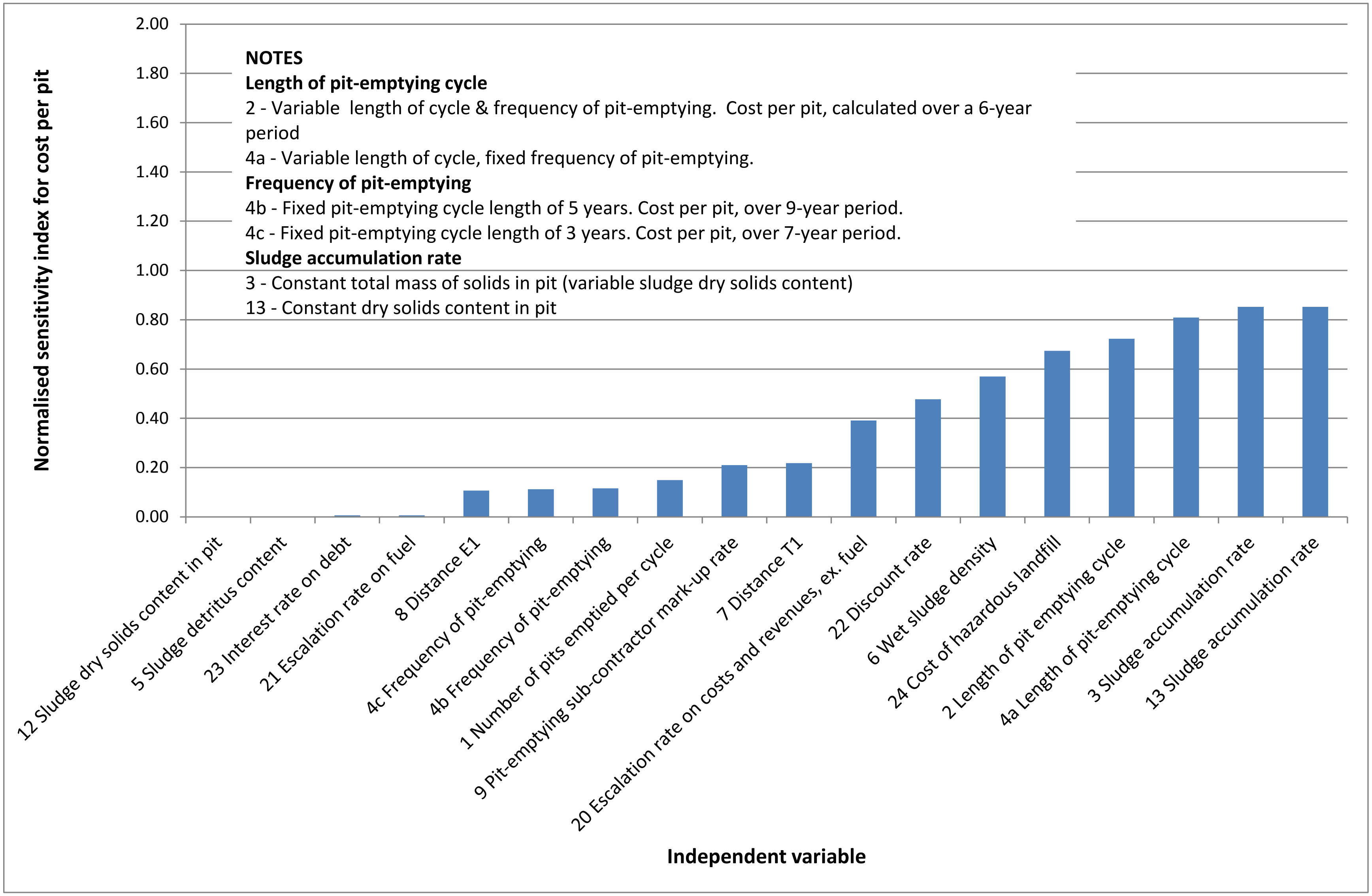

Chart 6.4: Normalised sensitivity index values for the cost per pit for disposal to landfill, sorted in ascending order

The following inputs showed the greatest level of difference in impact on the three disposal routes (i.e. a high divergence between the three SI_N values)[6]:

- The number of pits emptied per cycle;
- The sludge accumulation rate, when a constant mass of dry solids is maintained in the pit;
- The wet sludge density;
- The dry solids content of the sludge in the pit, when sludge accumulation rate remains constant;
- The cost of hazardous landfill.

The detailed reasons for the differing impact of the input variables on the costs of disposal, and the variations in sensitivities for the different methods, are discussed in section 8, under the general application of the model. Brief comment is made here on the variables with greatest impact on the model outputs.

In sensitivity case 2, the length of the pit-emptying cycle is equal to the frequency with which each pit in an area is emptied. The much higher sludge disposal costs for shorter cycles reflect the dominating influence of the fixed costs associated with each pit-emptying (independent of the quantity of sludge removed from the pit at each emptying). At pit-emptying cycle lengths of three years or more, the cost becomes far less sensitive to changes in cycle length - see Chart 6.5.

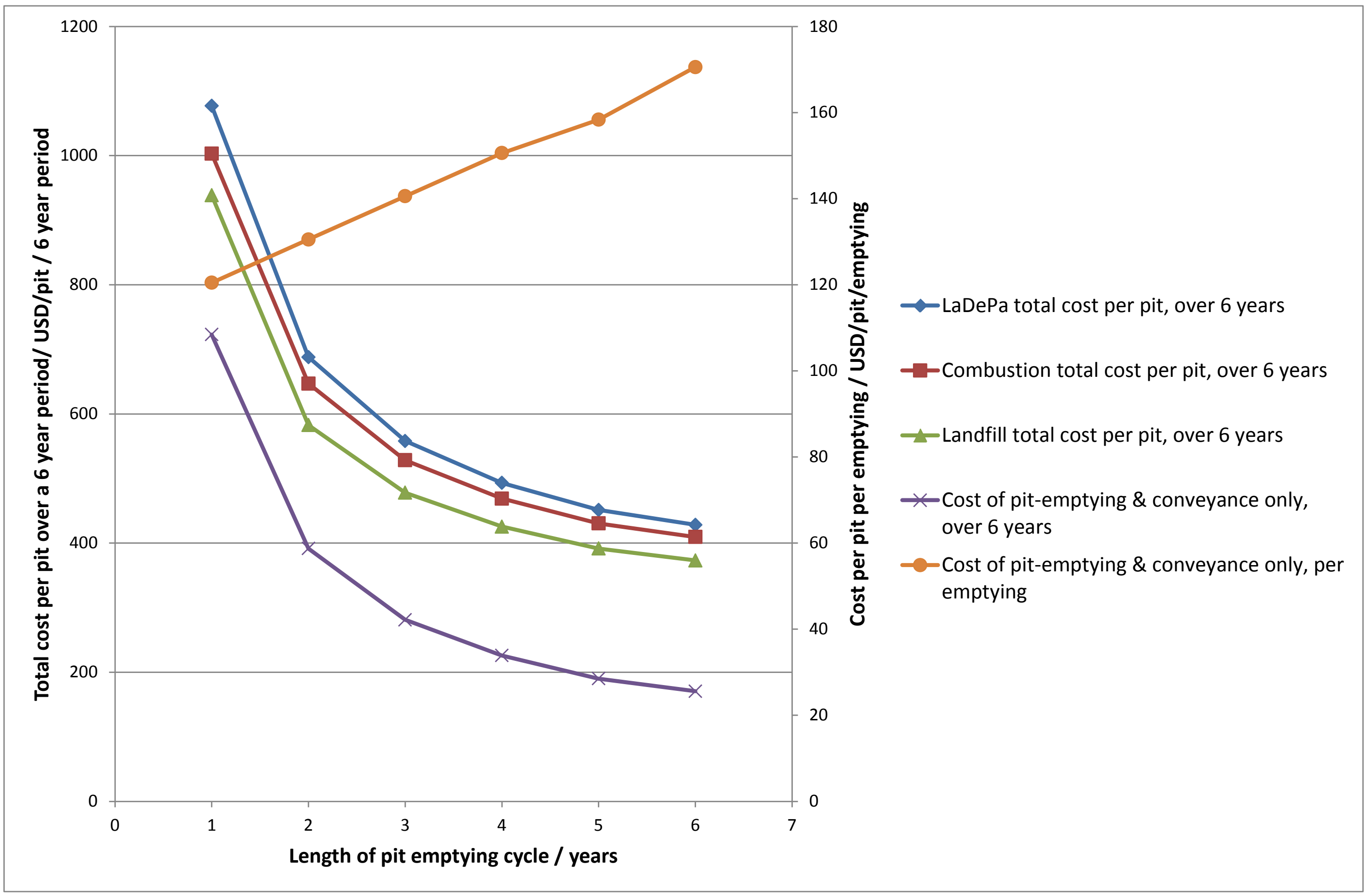

Chart 6.5: Variation of cost per pit with the length of pit emptying cycle

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[6] Note that the SI_N values for financial rates (interest rate, discount rate, escalation rates) cannot be compared between combustion and the other two methods, as the cash flow period used for combustion was 20 years, and only 10 years for the LaDePa process and landfill.

When the frequency of pit-emptying is maintained constant at 5 years, and the length of pit-emptying cycle varied (sensitivity case 4a), the model outputs are even more sensitive to changes in the length of pit-emptying cycle. This can be seen by comparing the SI_N values for cases 2 and 4a on Chart 6.1.

The strong influence of the sludge accumulation rate in pits, and thus the volume of sludge to be processed (even when the total mass of solids remained constant) are logical, as costs of conveyance are directly correlated to volume of sludge. The LaDePa capacity required, and therefore cost, is directly tied to the volume of sludge processed. Whilst required combustion capacity is dependent on the total mass of dry solids in the feed, rather than volume, costs will increase for feeds with a lower concentration of solids in them, because of higher supplemental fuel requirements. Landfill is charged by wet mass quantity and is therefore also directly correlated to the volume of sludge going to disposal.

7 Endproduct valuation

The model considered the potential market value of both the LaDePa pellets and combustion ash, for several different end uses, including agricultural applications and as feed additives to the opposite process (e.g. LaDePa pellets into combustion).

The bases used for the endproduct valuations were as follows:

- For fertiliser end-uses:
    - Valuation based on NPK nutrient content of sludge endproduct and selling prices of other fertilisers;
    - Assessing the economic value of replacing conventional fertilisers with LaDePa pellets, through partial budget analysis.

- For combustion end uses:
    - Valuation based on sludge endproduct calorific value.

Valuation of sludge endproducts for use as construction materials was not carried out.

The Phase 3 report (given in Appendix 3) covered the agricultural economic assessment of the LaDePa pellets in detail and will therefore not be included again here other than to highlight the main aspects taken into account in the development of the model.

The endproduct value of the LaDePa pellets or combustion ash is strongly dependent on composition – nutrient content and calorific value – which in turn is dependent on the composition of the feed sludge and the process conditions. Therefore the model outputs for endproduct values presented in this report cannot be taken as absolute values or applied generally – they represent results obtained for a particular batch of LaDePa pellets or ash in a specific context.

An important aspect, which is not taken into account in the model and the analysis in this report, are the other environmental benefits from making use of the LaDePa pelletiser or a total combustion process compared to other disposal methods for sludge. These include:

- Long-term improvements in soil fertility;
- Reduced risk of environmental degradation through the incorrect disposal of pit sludge;
- The benefits of the development of an integrated system of wastewater, sludge and agriculture.

A summary of the laboratory analyses carried out on the LaDePa pellets and combustion ash are provided in this section in order to demonstrate the data required for the endproduct valuation calculations in the model. Full data sets are given in Appendix 11.

7.1 Analysis results

An assessment of the endproducts from the LaDePa machine (pellets) and the combustion process (ash) was undertaken in order to determine their physical characteristics, nutrient content (micro and macro) and the presence of any parasites.

7.1.1 LaDePa pellets

The full data set of results from the analysis of the LaDePa pellets is given in Appendix 11, with a summary of the key data used in the spreadsheet model given in Table 7.1 and Table 7.2.

Table 7.1: Physicochemical data summary for LaDePa pellets

Analytical test	Unit	Average	SD	Reason for analysis
General				
Dry solids	g DS / g sample	0.8552	0.0136	Required for model calculations. Required by DAFF[1] for fertiliser products (water content must not exceed 400 g/kg)
Volatile solids	g VS / g sample	0.1617	0.0073	Required to calculate ash content which is required by DAFF for a fertiliser product
Ash content (fixed solids) - calculated	g FS / g sample	0.6935	0.0121	Required by DAFF for product (ash content must not exceed 670 g/kg)
Total suspended solids	g TSS / g sample	0.00048	0.00011	
Density – ground pellets	kg / m^3	877		Required for model calculations
Bulk density	kg / m^3	615		
COD	mg COD / g dry sample	82.20	21.42	Measure of organic content
pH	pH	6.37	0.22	Required by sludge utilisation and disposal guidelines[2] vol. 2 for product
Detritus	Present / absent	Present		Impact on LaDePa process throughput, pre-treatment requirements, calorific value of feed to combustion
Pellet size (diameter)	cm	0.58	0.11	DAFF regulations require product to pass through 12 mm sieve
Odour	Present / Absent	Absent		Required by DAFF regulations for product
Thermal				
Calorific value	MJ / kg sample	4.3821	0.2830	Fuel value
Thermal conductivity	W / m.K	0.1224	0.0156	Parameter for future drying & combustion calculations (not currently used)

[1]DAFF – Department of Agriculture, Forestry and Fisheries (Government of South Africa) – Regulations regarding fertilisers (DAFF 2012)
[2]Guidelines for the utilisation and disposal of wastewater sludge Volume 2 (Snyman & Herselman 2006)

Particle Separation Services (PSS) (the manufacturers of the LaDePa plant) advertise that a product dry solids content of 90 %DS can be achieved. Previous users of the LaDePa plant estimated the dry solids content of the product as 60 %DS. The measured solids content of one batch of pellets was 85.5 %DS. It appears that significant variation can be expected in the pellet dry solids. This is to be expected, as the endproduct dry solids will be dependent on the feed sludge composition, process conditions, endproduct storage conditions, and storage time.

Calorific value of the pellets tested (4.38 MJ/kg) was relatively low if the pellets were to be used as a fuel feed to an incinerator. As a comparison, the average calorific value of the raw VIP sludge sampled was 12.35 MJ/kg, and the calorific value of a fuel oil (typical supplementary fuel for incineration) is 41 MJ/kg. The benefit of the pellets is that they are clearly much drier than raw sludge.

Nutrient analysis of the pellets was carried out by two different laboratories (Cedara Plant Laboratory and the Pollution Research Group, University of KwaZulu-Natal). The values chosen for use in the spreadsheet model are those given in Table 7.2. The first set of test results from Cedara were carried out in 2011 on pellets that had been stored for an unknown length of time (history not known) and the second set of Cedara tests were carried out in 2013, using the same pellets as were analysed in the PRG laboratories. All results are given in Appendix 11.

Table 7.2: Nutrient content of LaDePa pellets

	Result	Unit	Source of sample analysis
Sample	Stockpiled pellets – age unknown		
Total nitrogen (N)	9.0	g / kg	Cedara 2013[1]
Total phosphorus (P)	17.3	g / kg	Cedara 2013[1]
Total potassium (K)	1.8	g / kg	Cedara 2013[1]
Calcium (Ca)	27.6	g / kg	Cedara 2013[1]
Magnesium (Mg)	3.0	g / kg	Cedara 2013[1]
Boron (B)	0.0504	g / kg	PRG 2013[2]
Copper (Cu)	0.1136	g / kg	PRG 2013[2]
Molybdenum (Mo)	Not detected	g / kg	PRG 2013[2]
Zinc (Zn)	0.5076	g / kg	PRG 2013[2]

[1] *Plant Laboratory Analytical Services, KwaZulu-Natal Department of Agriculture (2013) – date of analysis 5/7/2013*
[2] *Pollution Research Group, University of KwaZulu-Natal (2013) – date of analysis 16/5/2013*

Significant variation in nutrient content was seen between the different sets of results. The reasons for these are not clear at this stage. The standard operating procedures from Cedara will be compared to those used by the PRG in order to understand where the differences could be occurring between these two laboratories. These results highlight the need for further testing of pellets to be carried out, of different ages and sludge sources, to provide a more accurate 'average' nutrient content (see Section 10).

The heavy metal content of the same batch of LaDePa pellets was also analysed. The results are given in Appendix 11. Significant concentrations of lead and mercury were detected (400 mg/kg for lead and 39.8 mg/kg for mercury), equalling or exceeding the levels permitted in fertiliser products in South Africa (400 mg/kg and 10 mg/kg for lead and mercury respectively (DAFF 2012)). This could be due to the disposal of items such as batteries into pits, but at this stage the reasons for these results are not known. This highlights the importance of having an understanding of the source of the feed sludge and the characteristics of the sludge used to produce the pellets. At this stage, the results are used for information only and for comparison to the applicable limits where sludge products are to be used as fertilisers.

The LaDePa pellets were also analysed for the presence of any parasites. This is important particularly if the pellets are to be used as fertiliser for crops. The parasites investigated included *Ascaris*, *Trichuris* and *Taenia,* amongst others. These are the parasites most likely to be found in sludge from the eThekwini municipality area. The concentration (i.e. number per gram sample) and physiological state (i.e. viable, dead, necrotic etc.) were determined.

A more detailed description of these parasites is given as follows:

- *Ascaris lumbricoides* is the giant roundworm of humans, the eggs of which are frequently found in VIP sludge.
- *Trichuris* spp. (could be either *T. trichiura* or *T. vulpis*, the former from humans, the latter from dogs). Humans may be infected with *T. vulpis* and it could also be present in sludge from UD toilets, originating from the soil that is added to the pit after defecation.
- *Taenia* sp. (could be either *Taenia solium* – the pork tapeworm; or *Taenia saginata* – the beef tapeworm).

The preliminary test results show the presence of potentially viable *Ascaris* and *Trichuris* eggs in the LaDePa pellets. This means that at the time of the analysis, the eggs were still intact. While this does not necessarily indicate that the eggs would develop further, they have to be reported as a potential risk. Once again, these tests need to be carried out on further pellet samples and the feed sludge in order to determine if the LaDePa operation destroys parasites. The full results from the analysis are given in Appendix 11. Section 10 describes in further detail the testing that would be required.

7.1.2 Combustion ash

The micro and macro nutrient content of ash from a local wastewater sludge incinerator (KwaMashu wastewater treatment works, eThekwini, South Africa) was analysed in order to obtain inputs for the model. The main results are shown in Table 7.3, with all data provided in Appendix 11.

Table 7.3: Nutrient content of combustion ash

	Result	Unit	Source of sample analysis
Sample	Combustion ash from KwaMashu fluidised bed incinerator		
Total nitrogen (N)	1.9	g / kg	Cedara 2013[1]
Total phosphorus (P)	11.9	g / kg	Cedara 2013[1]
Total potassium (K)	2.9	g / kg	Cedara 2013[1]
Calcium (Ca)	116.1	g / kg	Cedara 2013[1]
Magnesium (Mg)	6.3	g / kg	Cedara 2013[1]
Copper (Cu)	0.2	g / kg	Cedara 2013[1]
Zinc (Zn)	0.5	g / kg	Cedara 2013[1]

[1] *Plant Laboratory Analytical Services, KwaZulu-Natal Department of Agriculture (2013) – date of analysis 6/8/2013*

The analysis shows that the ash contains some macro nutrients that may be beneficial to plant growth. It should be noted that the ash resulted from the combustion of primary wastewater sludge, i.e. much fresher sludge than pit latrine sludge.

The original aim was to measure the nutrient content of the feed sludge to the incinerator, and the nutrient content of the corresponding ash. This would then provide an indication of the change in nutrient content expected if VIP sludge were to be incinerated, and thus an estimate of the VIP sludge ash nutrient content. It was not possible to analyse the incinerator feed sludge for its nutrient content as part of this work, therefore the effect of combustion on nutrient content has not been incorporated into the model.

7.2 Estimation of endproduct market value

An estimation of the market value of the endproducts was undertaken for two scenarios: (i) as a fertiliser and (ii) as a fuel. The results are discussed in the following sections.

7.2.1 Fertiliser products

7.2.1.1 Results

In order to obtain an estimate of the value of LaDePa pellets and combustion ash as fertiliser products, a pro-rata estimation was made in the following way:

- The value of pellets and ash when based on the inorganic fertiliser price by a direct scaling of the price of wholesale urea, MAP and KCl fertilisers, based on the quantity of NPK contained in the sludge endproducts compared to the quantities contained in the inorganic products.
- The value of pellets and ash when based on organic fertilisers calculates the value of the organic fertilisers based on their NPK content, and then calculates the mark-up from this value to their actual wholesale price. The same proportional mark-up is then applied to the NPK value of the LaDePa pellets and combustion ash. The mark-up is assumed to account for the additional benefits of other macro and micro-nutrients as well as carbon content in the organic fertilisers.

The full calculations are shown in worksheet 19 – Product valuation, within the spreadsheet model. Example results for this assessment for the eThekwini case are given in Table 7.4. Two example calculations are also provided in order to demonstrate the methodology used in the model.

Example 1: Calculation of the value of the LaDePa pellets based on the wholesale prices of inorganic fertilisers

(i) Calculate the price per unit mass of nutrient in a chosen inorganic fertiliser

Chosen fertiliser: Urea, 46%N
Wholesale price: 4820 LCU/tonne

$$Price\ of\ N = \frac{4820}{(1000 * (\frac{46}{100}))} = 10.48\ LCU/kgN$$

(ii) Calculate the prices of phosphorus and potassium calculated using the same method and wholesale prices for MAP and KCl fertilisers. This gave:

Price of P: 25.92 LCU / kg P
Price of K: 10.50 LCU / kg K

(iii) Calculate the value of each nutrient (N, P and K) in the LaDePa pellets. For example, for N:

N content of LaDePa pellets: 0.9%

$$Value\ of\ N\ in\ pellets = \%\ N\ content\ in\ pellets * 10 * Wholesale\ inorganic\ price\ of\ N$$

$$Value\ of\ N\ in\ pellets = 0.9\ x\ 10\ x\ 10.48 = 94.30\ LCU\ per\ dry\ tonne\ pellets$$

By similar calculations, the values of the P and K in the pellets are calculated as:

Value of P in pellets: 448.40 LCU/dry tonne pellets
Value of K in pellets: 18.90 LCU/dry tonne pellets

(iv) Add the value of the N, P and K:

$$Value\ of\ NPK\ in\ pellets = 94.30 + 448.40 + 18.90 = 562\ LCU\ per\ dry\ tonne$$

(v) Convert to a value per wet tonne (as sold) of pellets:

Dry solids content of LaDePa pellets: 85.5 %DS

$$Value\ of\ NPK\ in\ pellets\ as\ sold = 562 * \left(\frac{85.5}{100}\right) = 480\ LCU\ per\ tonne$$

This is equivalent to 48 USD / tonne LaDePa pellets.

Example 2: Calculation of the value of the LaDePa pellets based on the price of a bagged organic fertiliser

(i) Calculate the value of the N, P and K per dry tonne of organic fertiliser, using the values for unit mass quantities of N, P and K calculated in steps (i) and (ii) of Example 1

Chosen organic fertiliser: Natural Organic (chicken manure base)
Price: 9000 LCU/tonne (extrapolated from the price per 10kg bag)
N content: 3.43%
P content: 1.88%
K content: 3.62%

$$Value\ of\ N\ in\ organic\ fertiliser = 3.43 * 10 * 10.48 = 359\ LCU\ per\ dry\ tonne$$

Similarly, the value of the P and K in the organic fertiliser were calculated to be:

Value of P in organic fertiliser: 487.28 LCU / dry tonne
Value of K in organic fertiliser: 380.10 LCU / dry tonne

(ii) Calculate the total value of the NPK in the fertiliser per wet tonne:

$$Value\ of\ NPK\ in\ organic\ fertiliser = 359 + 487 + 380 = 1227\ LCU\ per\ dry\ tonne$$

Dry solids content of organic fertiliser: not specified, assumed 100 %DS

$$Value\ of\ NPK\ in\ organic\ fertiliser\ as\ sold = 1227 * \left(\frac{100}{100}\right) = 1227\ LCU\ per\ tonne$$

(iii) Calculate the sale price of the bagged fertiliser without the retailer's mark-up:

Mark-up assumed: 40%

Sale price: 9000 LCU / tonne

$$Sale\ price\ without\ markup = \left(\frac{100-40}{100}\right) * 9000 = 5400\ LCU\ per\ tonne$$

(iv) Calculate the percentage increase in price from the NPK content to the sale price of the organic fertiliser. This difference is assumed to account for the additional benefits of the organic fertiliser over the inorganic – organic carbon and micro-nutrients amongst others:

$$Percentage\ increase\ in\ price = \left(\frac{5400}{1227}\right) * 100 = 440\ \%$$

(v) Apply this percentage increase to the NPK value of the LaDePa pellets to obtain an estimated sale price for bagged sale of pellets (excluding retailer mark-up):

$$Sale\ price\ of\ dry\ LaDePa\ pellets = \left(\frac{440}{100}\right) * \ 562 = 2472\ LCU\ per\ dry\ tonne$$

$$Sale\ price\ of\ LaDePa\ pellets = 2472 * \left(\frac{85.5}{100}\right) = 2114\ LCU\ per\ tonne\ as\ sold$$

This is equivalent to 211 USD / tonne pellets as sold.

Table 7.4: LaDePa pellet and combustion ash market value estimations, based on different commercial fertiliser prices

Fertiliser product	Price	Units
Inorganic fertiliser – urea (46% N)	482	USD / tonne
Inorganic fertiliser – MAP (22%P, 10% N)	675	USD / tonne
Inorganic fertiliser – KCl (50% K)	525	USD / tonne
LaDePa pellets based on inorganic fertiliser nutrient prices	48	USD / tonne
Ash based on inorganic fertiliser nutrient content prices	36	USD / dry tonne
Organic fertiliser 1 price (bagged product sold in garden centre) (12% N, 3% P, 1.1% K)	875	USD / tonne
LaDePa pellets based on organic fertiliser 1 nutrient content and percentage increase in price above NPK value	358	USD / tonne
Organic fertiliser 2 price (bagged product sold in garden centre) (3.4 %N, 1.9 %P, 3.6 %K)	900	USD / tonne
LaDePa pellets based on organic fertiliser 2 nutrient content and percentage increase in price above NPK value	211	USD / tonne

This approximation indicates that a suitable bulk-price value for LaDePa pellets, based only on their NPK nutrient content, is USD 48 per tonne – a value that will obviously vary depending on the local context and commercial fertiliser prices. If the previous set of nutrient content results were used, this bulk-price value would only be in the region of USD 39 per tonne[7]. This again highlights the need for a greater number of pellet samples to be analysed in order to obtain a more representative value.

Ash is unlikely to be used as a standalone NPK fertiliser, because of its low NPK content and potential difficulties with application. However, it has potential as an additive to fertiliser products – for example as an additive to LaDePa pellets to boost nutrient content and increase the dry solids of the sludge feed to the LaDePa plant.

It is worth noting that there may be more benefit to using the LaDePa pellets or ash as a supplement to commercial fertilisers, based on the micro-nutrient content rather than for the NPK content. NPK values are relatively low, but significant levels of micro-nutrients are present. Further investigation into this aspect needs to be undertaken.

The actual price that LaDePa pellets can be sold at will also depend on the relative proportions of nutrients present and whether there is demand for the particular ratio present. Another major factor will be the relative costs of transport and product application of LaDePa pellets and/or ash, versus conventional fertilisers. This was considered in the second part of the product valuation, the financial assessment of using LaDePa pellets in place of conventional fertilisers (Section 7.3).

7.2.1.2 Sensitivity analysis

A sensitivity analysis was carried out on the product values, using the same method as described in section 6.2 for the costs. The values of parameters used for the base case are given in Table 7.5.

Table 7.5 Parameters used for the product value sensitivity analysis

Ref. no.[1]	Input variable	Value	Unit	Notes
26	Phosphorus price – price of 22% phosphorus MAP inorganic fertiliser	675	USD / tonne	Wholesale
25	Nitrogen price – price of 46% urea	482	USD / tonne	Wholesale
27	Potassium price – price of 50% KCl	525	USD / tonne	Wholesale
	Organic fertiliser 1 price	875	USD / tonne	Sold as small bags, includes mark-up
	Organic fertiliser 2 price (manure-based)	900	USD / tonne	Sold as small bags, includes mark-up
Outputs				
	Nutrient value of LaDePa pellets based on inorganic fertiliser prices	48	USD / tonne	
	Nutrient value of LaDePa pellets based on Organic fertiliser 1 price	358	USD / tonne	
	Nutrient value of LaDePa pellets based on Organic fertiliser 1 price	211	USD / tonne	

1 Reference numbers appear where a sensitivity analysis case was run for the variable. Other variables are included for information on the base case.

Chart 7.1 shows the sensitivity of the endproduct value calculated by this method to changes in the market price of each of the macro-nutrients N, P and K.

[7] The discrepancy between the LaDePa pellet value based on the first set of Cedara results given in this report (USD 39 / tonne) and the Phase 3 report (USD 30 / tonne) is due to a different source of inorganic nitrogen being used in the two calculations.

Based on the nutrient analyses carried out for this work, LaDePa pellets and ash contained a higher proportion of P than N or K, therefore the higher sensitivity of product value (based on inorganic fertiliser prices) to market price of P is to be expected.

For the sludge endproduct value based on organic fertilisers greatest sensitivity in product value was seen to variation in the market price of P. Sensitivity is dependent on the relative quantities of NPK present in the LaDePa pellets and in each of the organic fertilisers.

7.2.2 Fuel products

The potential value of LaDePa pellets as a feed to incineration was estimated based on the dry solids content and calorific value of the pellets. The cost of a conventional supplementary fuel – coal – was scaled relative to these two properties. Coal with a calorific value of 31 MJ/kg and dry solids content of 85 %DS, at a sale price of 73 USD/tonne was used. The scaled value of the pellets, with a calorific value of 4.32 MJ/kg and dry solids of 85.5 %DS was calculated as 10 USD/tonne.

The cost of producing the pellets (1 226 USD/tonne) is far higher than their fuel value, and significantly higher than the cost of conventional incinerator supplementary fuel (e.g. coal). The calorific value of the batches of pellets analysed is also too low for the pellets to be a viable supplementary fuel to an incinerator burning wet sludge. On the basis of the current calorific value analysis, it is unlikely to make economic sense to use the LaDePa pellets as a fuel source.

7.3 Economic viability of replacing conventional fertilisers with LaDePa pellets

7.3.1 Partial budget analysis results

The economic benefit of using LaDePa pellets on various crops, in place of conventional fertilisers, was estimated using a partial budget analysis. This is covered in detail in the Phase 3 progress report (Appendix 3a) and in the agricultural assessment spreadsheet (Appendix 3b). The benefits of replacing both a compound inorganic fertiliser and a chicken-manure-based organic fertiliser with LaDePa pellets were analysed.

The partial budget analysis used in the model takes into account the cost of the fertiliser, the distance that needs to be travelled and the cost of spreading. It is assumed that the reduced income and additional income from the change in fertiliser will be equal to zero.

A specific nutrient is chosen as the basis of the partial budget analysis: this is the nutrient where the crop demand will be satisfied by both fertilisers being compared. The other nutrients may however be under or over-applied. In the case of under-application, it may be possible to blend the LaDePa pellets with an additive to satisfy remaining demand for nutrients. Over-application of certain nutrients may be problematic depending on the crop being grown and soil conditions, and must be looked at case by case.

The partial budget analysis does not take into account the value of any other macro-nutrients other than N, P and K, or the value of micro-nutrients or carbon contained in the fertilisers. The value of these components may be significant for the LaDePa pellets and organic fertilisers, and requires further analysis.

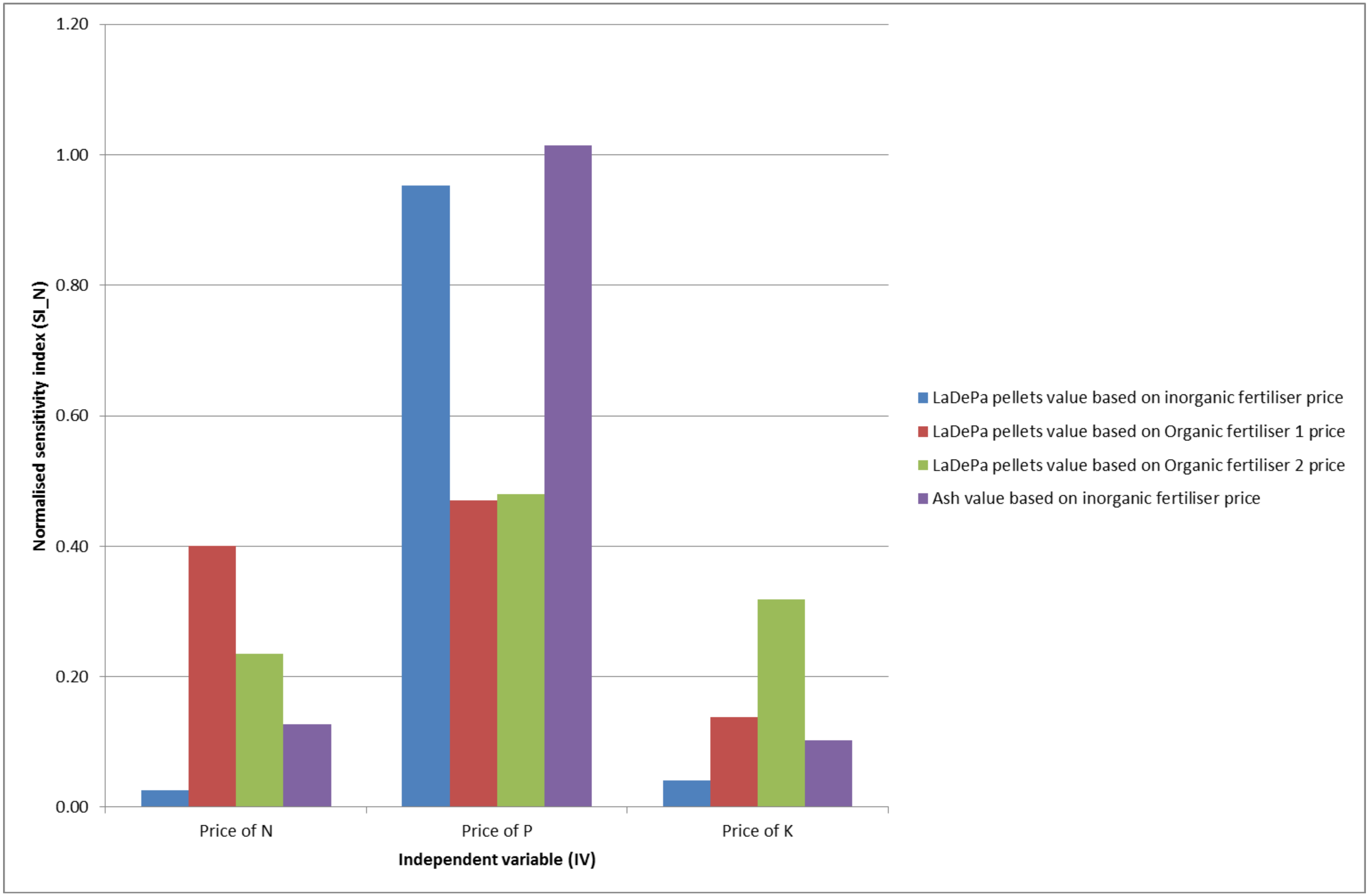

Chart 7.1: Sensitivity of estimated market value of LaDePa pellets and combustion ash as fertiliser products to changes in market price of N, P & K

The Phase 3 report and spreadsheet model did not take the transportation and storage costs into account, or the cost of land application (labour, equipment and machinery), or the cost of supplementary nutrients. The results presented in the Phase 3 report should therefore be taken as an initial assessment during the development of the model, and the results presented in this section taken as an updated analysis.

The revised partial budget analysis included in the model therefore takes into account the nutrient content of the fertilisers (and therefore the quantity required), transport costs and fertiliser spreading costs. It calculates the maximum price that LaDePa pellets could be sold at to be able to compete economically with conventional organic and inorganic fertilisers. An example of the use of the model to undertake a partial budget analysis is discussed in the following paragraphs.

The analysis was run for using LaDePa pellets instead of a compound inorganic fertiliser (3:2:1 (25%) + 0.5% Zn) for a dry beans crop. The price of the inorganic fertiliser was 478 USD/tonne. Equal transport distances were assumed. The spreading cost for conventional fertiliser was taken from literature (0.04 USD/kg from Victoria State Government 2013). Spreading cost for LaDePa pellets was assumed to be slightly higher, to cover the cost of any equipment modifications required (0.05 USD/kg).

When nitrogen was chosen as the basis for the pellet application rates, this resulted in an over-application of P and slight under-application of K. The results from the model indicated that the LaDePa pellets were never economically beneficial when compared to the inorganic fertiliser.

When phosphorus was chosen as the basis of the analysis (resulting in significant under-application of N and K when using LaDePa pellets), the results showed that the LaDePa pellets could compete with the inorganic fertiliser when sold at 37 USD/kg. However, this does not account for N and K being under-supplied when LaDePa pellets are used.

A fairer comparison is to factor in the cost of using an additive to the LaDePa pellets to supply the remaining N or K demand. Combustion ash (with significant K content) was chosen as the additive, leaving only N slightly under-supplied. On this basis, the LaDePa-additive combination was not competitive with the conventional inorganic fertiliser.

The analysis was run for a second time, considering replacing a chicken-manure-based organic fertiliser (3.43% N, 1.88% P, 3.62% K) with LaDePa pellets for the same dry beans crop. The selling price of the organic fertiliser was set at 200 USD/tonne (wholesale price estimated from a small bag retail price). Spreading costs and delivery distance were assumed to be the same as for the inorganic fertiliser. All LaDePa values were as previously. With the nutrient basis for the analysis chosen to be P, the maximum competitive wholesale sale price for LaDePa pellets was calculated as 18 USD/tonne. It should be noted that N and K were being somewhat over-supplied with the organic fertiliser, and under-supplied with the LaDePa pellets.

The price of 18 USD/tonne (and probably lower given that supplementary products would be required to satisfy the N and K demands of the crop), is significantly lower than the LaDePa wholesale value which was calculated based on its nutrient content alone (48 USD/tonne – Section 7.2.1.1). This highlights the significant impact that the transport and spreading costs have on the economic viability of using sludge endproducts as fertilisers.

7.3.2 Sensitivity of LaDePa pellet competitive selling price to model inputs

The maximum price for which the LaDePa pellets can be sold for in order to be able to compete with existing fertilisers is referred to as the ‘competitive selling price’. The sensitivity of this price to changes in the input costs was carried out, using the method described in Section 6.2. The input parameters used for the based case are given in Table 7.6. Chart 7.2 summarises the sensitivity of this competitive selling price to the input factors.

Table 7.6: Base case values for the parameters used in the sensitivity analysis on the competitive selling price for LaDePa pellets

Ref. no.[1]	Input variable	Value	Unit	Notes
	Phosphorus price – price of 22% phosphorus MAP inorganic fertiliser	675	USD / tonne	
	Nitrogen price – price of 46% urea	482	USD / tonne	
	Potassium price – price of 50% KCl	525	USD / tonne	
28	Distance from LaDePa plant to farm site where pellets applied to land	25	km	
29	Spreading costs for LaDePa pellets	0.5	USD / kg	Labour & equipment for spreading on land
30	Wholesale price for organic, manure-based fertiliser	200	USD / tonne	cf. value of NPK content USD 123 / tonne
31	Wholesale price for inorganic compound fertiliser	478	USD / tonne	
32	Nutrient on which to base partial budget analysis for LaDePa pellets	P	nutrient	
	Outputs for base case			
	LaDePa pellet calculated sale price for their application to have the same overall costs as conventional inorganic fertiliser application	-83	USD/tonne	Negative figure – i.e. LaDepa pellets never competitive for base case scenario
	LaDePa pellet calculated sale price for their application to have the same overall costs as conventional organic fertiliser application	18	USD/tonne	

1 Reference numbers appear where a sensitivity analysis case was run for the variable. Other variables are included for information on the base case.

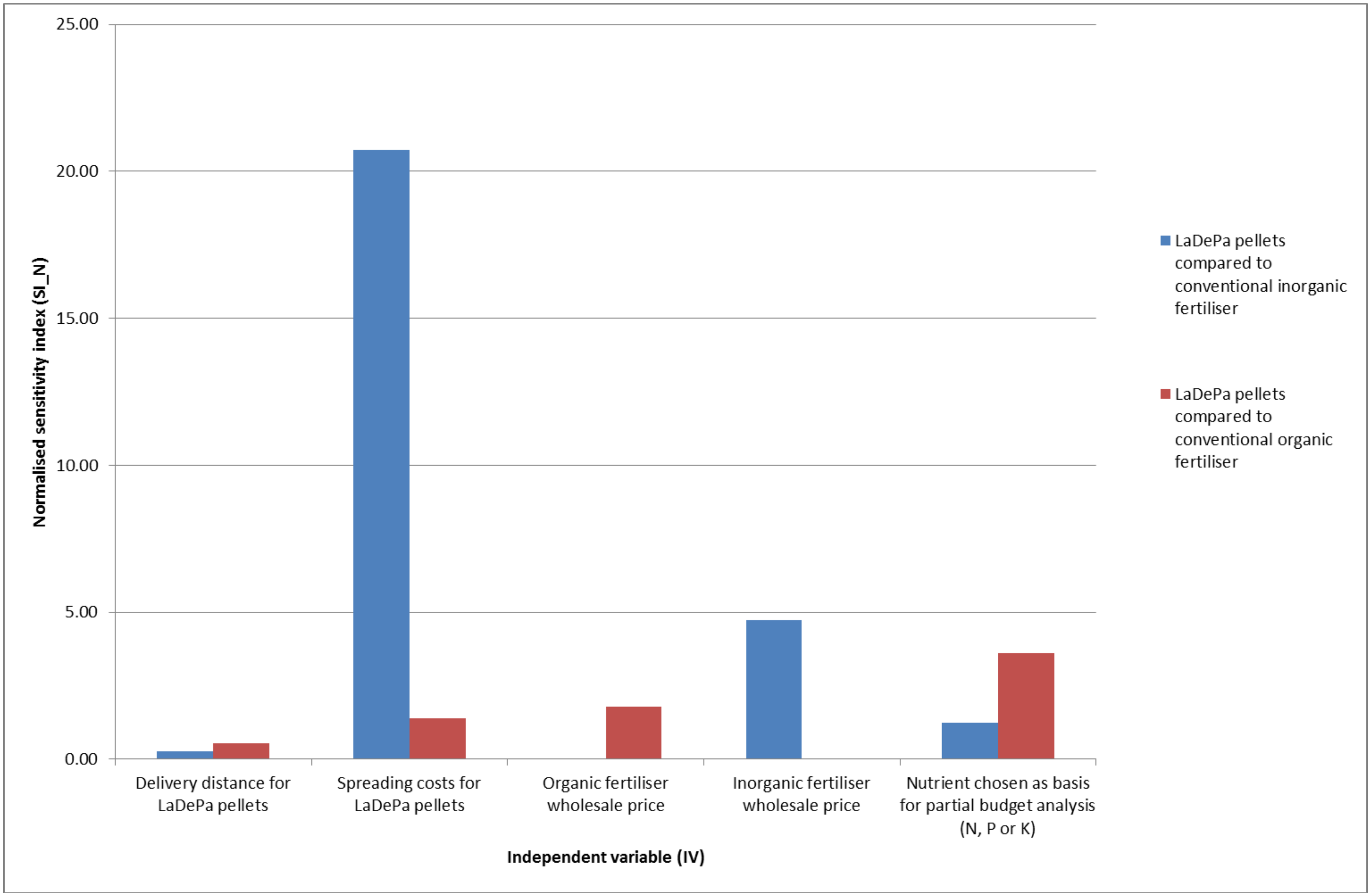

Chart 7.2: Sensitivity of maximum competitive selling prices of LaDePa pellets to inputs to the partial budget analysis

When comparing the use of LaDePa pellets to inorganic fertiliser, the spreading cost per kg of fertiliser was the input with the most significant impact. This can be explained by the relative volumes of fertiliser that would need to be applied to one hectare of crop in order to satisfy the crop P requirements; i.e. 300kg of conventional inorganic fertiliser compared to 1 690kg of LaDePa pellets.

However, when a comparison was made to the use of organic fertiliser, the partial budget analysis, resulted in similar quantities of LaDePa pellets and organic fertiliser being required (based on P). Therefore changes to delivery distance and spreading costs had similar proportional impacts on the overall costs of using both these fertilisers.

The cost of the organic fertiliser was under 50% of the price of inorganic fertiliser (0.2 USD/kg v. 0.48 USD/kg), therefore changes to the organic fertiliser's price had a lower impact on the break-even price of LaDePa pellets than changes to the price of the inorganic fertiliser.

The partial budget analysis is based on fulfilling the crop requirements for either N, P or K. Changing the basis of the analysis impacts on the relative advantage of using LaDePa pellets over conventional inorganic or organic fertilisers. The LaDePa pellets (with ash additive to satisfy the crop K demand) always cost significantly more to use than the inorganic fertiliser, for any nutrient basis to the partial budget analysis. LaDePa pellets were competitive with organic fertiliser when P was the basis of the analysis, but not with N or K as the basis. Therefore the sensitivity of the break-even price to the nutrient basis for LaDePa pellets v. organic fertiliser was somewhat higher than for LaDePa pellets v. inorganic.

The following section of the report focuses specifically on the application of the model to the case of faecal sludge management in eThekwini municipality, South Africa.

8 General application of the model

The model was run using the data from the eThekwini context, with the aims of:

- Assessing the economic viability of the LaDePa process and fluidised bed incineration as pit latrine sludge disposal routes under normal operating conditions;
- Investigating at a basic level how the LaDePa process and fluidised bed incineration could become more economically viable in the eThekwini context if operating conditions were changed;
- Assessing the key aspects that could impact on the LaDePa process as a disposal route being an economically viable, replicable model for other locations.

The specific costs given in this section are clearly only applicable to the set of input parameters used for the eThekwini case, however the observations on the relationships between parameters show how different disposal methods can become more cost-effective as the environmental and financial conditions are changed.

8.1 Results from the base case model

Table 8.1 shows the results summary produced by the model when running with the eThekwini data set under normal operating conditions, i.e. the 'base case' scenario. The worst case that is assumed is that all sludge would be disposed of to hazardous landfill.

Under these conditions, the costs per pit emptied for the three disposal routes are calculated as follows:

LaDePa	376	USD/pit
Combustion	359	USD/pit
Landfill	326	USD/pit

Pit size is measured on a volumetric basis. The costs per tonne of dry solids removed from pits are as follows:

LaDePa	1 147	USD/dry tonne
Combustion	1 095	USD/dry tonne
Landfill	995	USD/dry tonne

There is a 13% difference in cost between disposal via processing through the LaDePa, the most expensive option, and disposal to landfill, the cheapest. On the basis of 35,000 pits requiring emptying on a 5-year cycle this amounts to a 1,750,000 USD cost difference. This is a significant cost, but one that could still be off-set by other factors, financial and otherwise. These are explored in the following sections.

8.1.1 Product value

The levelised costs to produce the LaDePa and combustion endproducts were calculated by the model to be:

LaDePa	1 226	USD/tonne LaDePa pellets
Combustion	2 101	USD/dry tonne ash

In comparison, the fertiliser NPK value of the products was calculated as:

Pellets	48	USD/tonne LaDePa pellets
Ash	36	USD/dry tonne ash

It is clear that the fertiliser value of the endproducts does not cover the cost of production. The true endproduct values will be even lower, as market price reflects the value of the products for a specific application when compared to existing products. When the LaDePa endproduct value takes into account the higher implied transport and spreading costs, its value drops to possible 18 USD/tonne[8].

Based on the data entered into the model, approximately 2 100 tonnes of pellets are produced per pit-emptying cycle. If the pellets could be sold at 18 USD/tonne this would raise only 38,646 USD/cycle in revenue. Based on the cost calculations presented earlier, this is clearly in-sufficient to cover the cost difference between disposal using the LaDePa process or disposal to landfill.

Although the NPK concentrations in LaDePa pellets are significantly lower than in commercial organic fertilisers, the pellets do contain significant levels of micro-nutrients beneficial to crops and organic carbon beneficial to soils. The return of all these components to the soil is therefore a benefit of the LaDePa process over the other two routes. LaDePa pellets are also potentially easier to apply directly to land than combustion ash. It also avoids the generation of greenhouse gases from both combustion and landfill. Neither of these impacts has been quantified within the model, but are significant factors in choice of disposal route.

8.1.2 Capital investment required

In the eThekwini context, the LaDePa plant is leased rather than purchased, and the capital investment required for the combustion disposal route is therefore significantly higher in comparison, i.e. 7.3 million USD for combustion compared to 132 000 USD for LaDePa (with the LaDePa plant leased). These figures exclude capital investment required for the emptying and conveyance processes.

Depending on municipal budget structures and loan arrangements, a lower capital option may be preferable, even if more expensive overall.

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[8] Calculated for a dry beans crop where LaDePa pellets were used to replace a commercial organic fertiliser.

Table 8.1: Model outputs for eThekwini at base case conditions

RESULTS - UNITED STATES DOLLARS (USD)					
	LaDePa	**Combustion**	**Landfill (base case)**	**Units**	**Comments**
Currency: USD					
Number of households served per pit emptying cycle		35 000		Total number per pit-emptying cycle	
Sludge removed from pit emptying area annually		2 294		Tonnes dry solids / year, including detritus	
Planning horizon	10	20	10	years	This is the period that LaDePa & combustion cash flow sheets and the NPV are calculated for.
Total cost of sludge disposal (emptying, conveyance and processing via chosen route)					
Is the cost of emptying and conveyance included?	Yes	Yes	Yes		
Levelised cost of pit-emptying & sludge disposal per dry tonne FS	1 147	1 095	995	USD / dry tonne FS	Includes managing contractor & service provider costs. Based on mass arriving at storage tanks at the LaDePa / combustion site
Levelised cost of pit emptying & sludge disposal per pit	376	359	326	USD / pit	Includes managing contractor & service provider costs
Levelised cost to produce product	1 226	2 101	N/A	USD / tonne product	LaDePa pellets (as is) or dry tonnes of combustion ash. Includes managing contractor costs
Total initial capital investment in LaDePa / combustion process (excludes emptying & conveyance)	132 500	7 319 500	N/A	USD	For storage, pre-treatment, LaDePa/combustion process, product & by-product disposal
NPV	-23 697 067	-48 215 398	-22 173 351	USD	
Project IRR	N/A	N/A	N/A	%	Array must contain at least one positive and one negative value for IRR to be calculated
Equity IRR	N/A	N/A	N/A	**%**	Array must contain at least one positive and one negative value for IRR to be calculated

RESULTS - UNITED STATES DOLLARS (USD)					
	LaDePa	**Combustion**	**Landfill (base case)**	**Units**	**Comments**
Costs of emptying & conveyance only					
Levelised cost of pit emptying & conveyance per dry tonne FS		483		USD / dry tonne FS	Includes sub-contractor mark-up
Levelised cost of pit emptying & conveyance per pit		158		USD / pit	Includes sub-contractor mark-up
Product					
Possible fertilizer value of product based on non-organic fertilizer NPK value	48.0	35.9	N/A	USD / tonne	
Annual quantity of product	2 146.67	1 195.43	N/A	tonnes / year	Wet tonnes of LaDePa pellets or dry tonnes of combustion ash. Includes managing contractor costs
Operational parameters					
Percentage reduction in tonnes of waste going to landfill	81.0	63.7	0	%	
Time taken to process sludge from one pit-emptying cycle through LaDePa or combustion	5.00	5.00	N/A	years	
Annual fossil fuel energy used	5 699	61 660	1 162	GJ / year	NOTE: Combustion supplemental fuel use is based on (i) no energy recovery at the incinerator and (ii) calculation based on feed dry solids content and the consequent minimum feed calorific value required. Further refinement of calculation required.
Combined mass of NPK produced in product	51.57	19.96		tonnes NPK / year	NOTE: currently not comparable for eThekwini case - based on analysis of pellets and ash, from different sludge sources.
COD reduction across process				Tonnes COD removed from environment / year	Environmental benefit. To be determined when further testing has been completed.

RESULTS - UNITED STATES DOLLARS (USD)					
	LaDePa	**Combustion**	**Landfill (base case)**	**Units**	**Comments**
Agricultural value of product					
Value based on non-organic fertilizer prices and NPK content	48	36	N/A	LCU / tonne	Per wet tonne of LaDePa pellets or dry tonnes of combustion ash.
Value based on organic fertiliser 1 price and NPK content	358	N/A	N/A	LCU / tonne	Per wet tonne of LaDePa pellets or dry tonnes of combustion ash.
Value based on organic fertiliser 2 price and NPK content	211	N/A	N/A	LCU / tonne	Per wet tonne of LaDePa pellets or dry tonnes of combustion ash.
Economic feasibility of replacing conventional fertilisers with LaDePa pellets					
Principal nutrient to be supplied to crop (basis for partial budget analysis)	P	N/A	N/A	Nutrient	
Selling price of LaDePa pellets where the costs of using commercial INORGANIC **fertiliser and LaDePa pellets are equal, for the chosen nutrient**	-83	N/A	N/A	USD / wet tonne	LaDePa pellets must be sold below this price if they are to compete with conventional fertiliser. If price is negative, LaDePa pellets are not competitive.
Is it economic to use LaDePa pellets instead of the inorganic fertiliser if they are sold at a price that reflects their NPK nutrient content?	No	N/A	N/A		
Principal nutrient to be supplied to crop (basis for partial budget analysis)	P	N/A	N/A	Nutrient	
Selling price of LaDePa pellets where the costs of using commercial ORGANIC **fertiliser and LaDePa pellets are equal, for the chosen nutrient**	18	N/A	N/A	USD / wet tonne	LaDePa pellets must be sold below this price if they are to compete with conventional fertiliser. If price is negative, LaDePa pellets are not competitive.
Is it economic to use LaDePa pellets instead of the organic fertiliser if they are sold at a price that reflects their NPK nutrient content?	No	N/A	N/A		

8.1.3 Reduction in waste going to landfill

Use of the LaDePa process results in a 81% reduction of mass of waste going to landfill, compared to a 64% reduction for combustion. Environmental issues associated with landfills (management of leachate and landfill gas) are consequently reduced in proportion. This distinction between LaDePa and combustion will become increasingly more financially important as landfill legislation tightens, available capacity decreases, and gate fees increase.

8.1.4 Carbon emissions

Under the current conditions, the combustion process has the highest carbon emissions as the carbon in the sludge is released on burning, and there are high supplemental fuel requirements. If the minimum acceptable dry solids in the feed to combustion were raised, supplementary fuel requirements would decrease. Costs would be incurred from the pre-drying process, but the energy source for this could be solar (drying beds) or from recovering energy from the incineration off-gases. Carbon emissions for combustion will always be higher than for the other two processes, but could potentially be significantly reduced from their current calculated levels.

8.1.5 Social benefits

The use of local LaDePa plants may create a greater number of accessible jobs than the use of one centralised incineration plant. More of the incineration plant jobs may require a higher level of technical training, and the plant will only provide jobs in one area. LaDePa plants will be distributed across several different areas, and jobs are likely to be accessible to people with lower technical skills (but still provide an opportunity to be trained up).

8.2 Optimising the economics of LaDePa and combustion

Section 6 of the report considered the sensitivity of outputs from the model to selected model inputs. This analysis showed the relative scale of influence of different input parameters on the calculated costs of sludge disposal, however it did not explore the nature of the correlations between input and output parameters. This section provides an overview of the input-output relationships, to provide a basis for considering how operating conditions could be modified in order to make the use of the LaDePa process and/or combustion more cost-effective options for sludge disposal. Each section considers the variation in costs of sludge disposal with changes to a different input variable.

8.2.1 Number of households served

The number of households served is taken to be equivalent to the number of pits emptied per cycle, as the model assumes that on average there is one pit latrine per household.

The results of this analysis is shown in Chart 8.1.

Landfill costs remain approximately constant – the slight decrease in costs with increasing number of households is due to economies of scale in the emptying of pits and transport of sludge.

Combustion costs decrease with increasing numbers of pits, as for the size of combustion plant modelled only one plant is ever required, and there is less unused capacity with higher numbers of pits.

Costs of LaDePa decrease, but discontinuously, as the number of plants required varies step-wise. Higher costs are incurred where plants are being run with significant spare capacity.

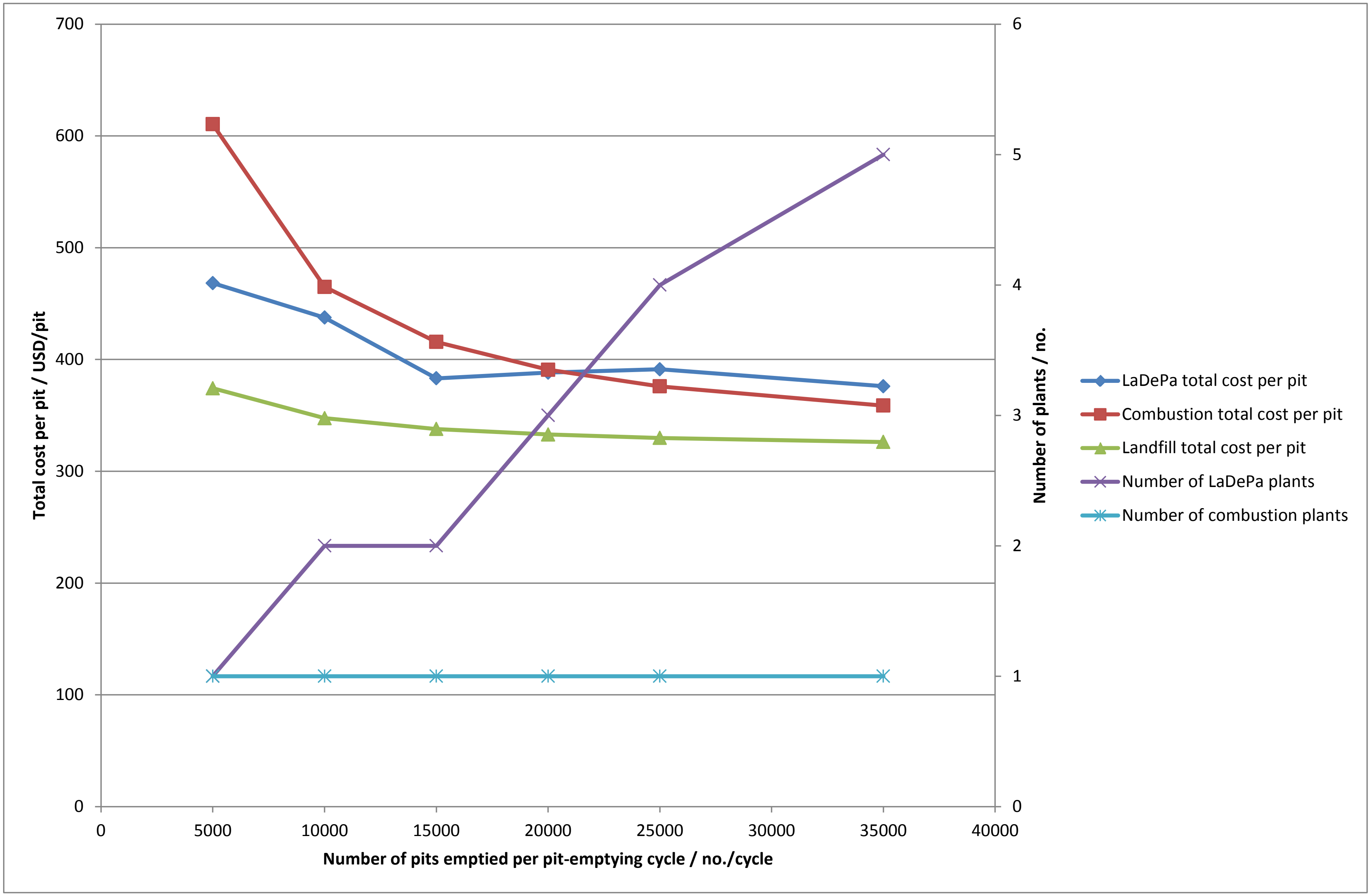

Chart 8.1 Variation of costs per pit with the number of households served by the pit-emptying programme

8.2.2 Structure of the pit-emptying programme

Figure 8.1 gives examples of pit-emptying programme structures, to clarify the terminology used in the sections below.

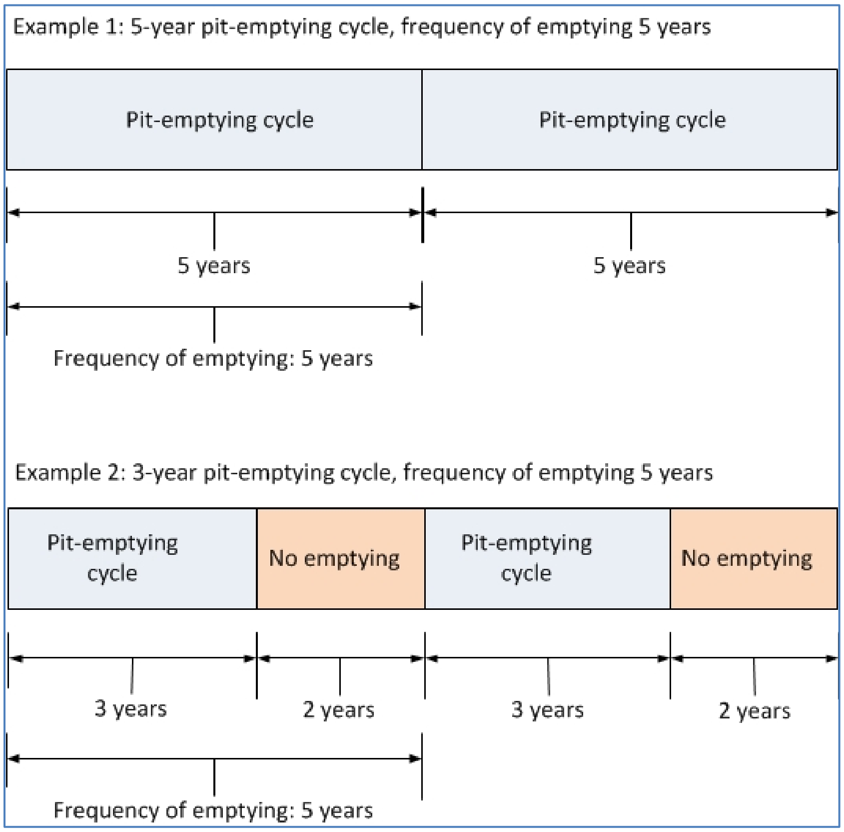

Figure 8.1: Examples of different pit-emptying cycle structures

The pit-emptying cycle is the length of time over which pits are emptied. Consecutive pit-emptying cycles may follow on directly from one another, or a gap may be allowed between them. The frequency of pit-emptying refers to the time between emptying services for a given pit. The impact that the lengths of these different parts of the pit-emptying programme have on costs is investigated here.

8.2.2.1 Length of the pit-emptying cycle: no gap between cycles, variable frequency of emptying

Chart 8.2 shows the total cost per pit, over a six-year period, for pit-emptying cycles ranging in length from one year to 6 years. For all cases it was assumed that there was no gap between pit-emptying cycles (as in Example 1, Figure 8.1). Therefore for a pit-emptying cycle length of two years, three cycles would be carried out during a six-year period (i.e. every pit would be emptied three times). Since the total number of pits remained constant, the total volume of sludge processed per year remained constant. This variable tests the competing influences of the fixed costs per pit-emptying versus the costs that vary depending on how much sludge is removed from a pit, on the overall cost of sludge disposal – i.e. is it advantageous to empty 'a little and often'.

For the set of input parameters chosen, the cost per household over six years was far higher for short pit-emptying cycles, reflecting the dominating influence of fixed costs of each pit-emptying. For pit-emptying cycle lengths of three years or more, the cost per household was far less sensitive to the length of cycle.

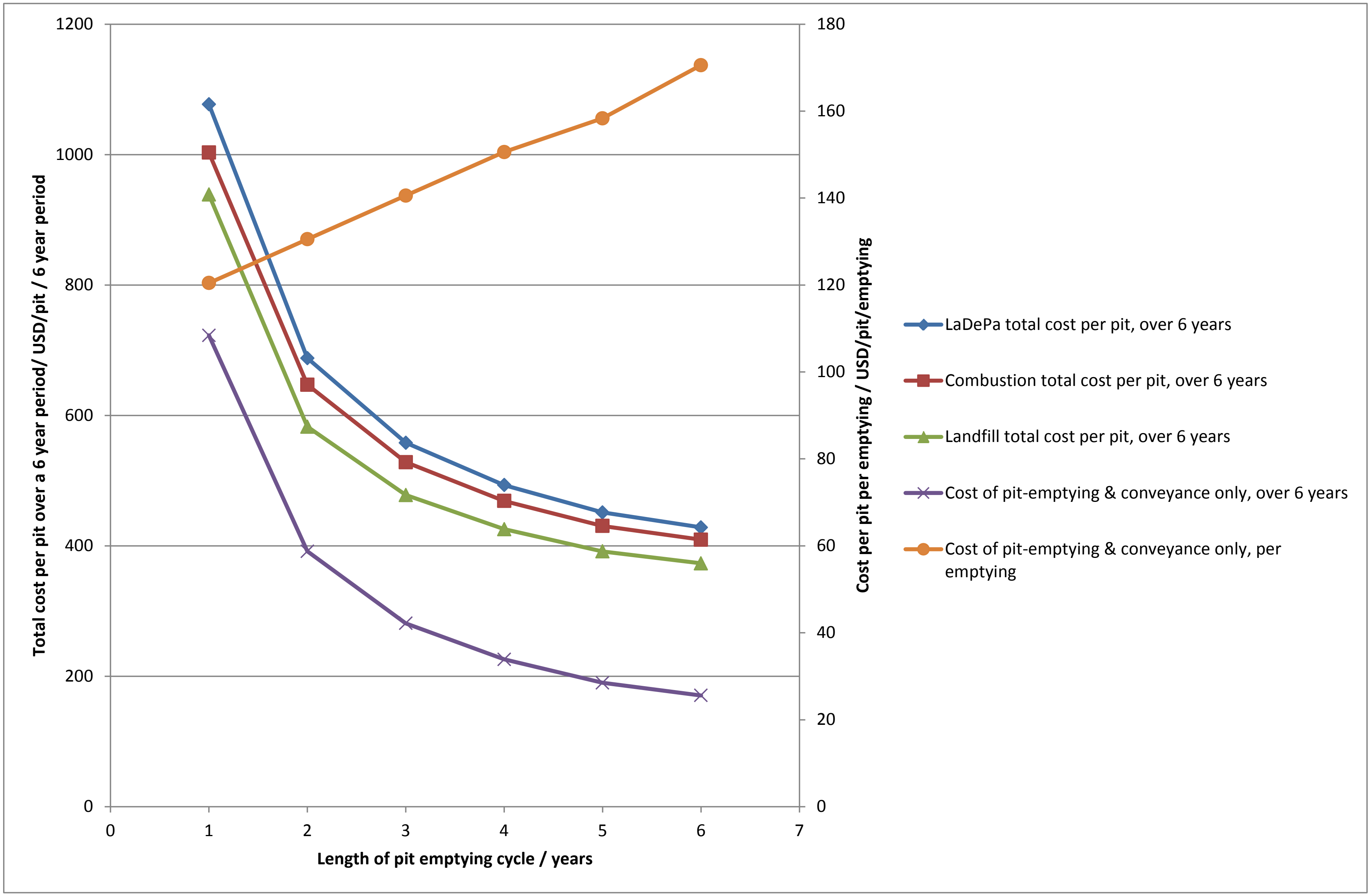

Chart 8.2: Variation of the cost per pit with the length of the pit-emptying cycle (variable frequency of pit-emptying)

8.2.2.2 Length of pit-emptying cycle: gaps between cycles, fixed frequency of emptying

Sludge may be stockpiled and processed via the LaDePa process or combustion after the pit-emptying cycle has finished, until the next pit-emptying cycle starts.

For this analysis, the frequency of pit-emptying was fixed at 5 years. The time between pit-emptying cycles was varied between zero and four years, thus the time between cycles varied proportionally. For a fixed number of pits, the time allowed between pit-emptying cycles has no impact on the number of LaDePa or combustion plants required, as the volume of sludge accumulating in the pits increases in proportion to the frequency of pit-emptying. As in Chart 8.2, this analysis again tests the impact of varying the length of the pit-emptying cycle, but without also varying the frequency of emptying.

Chart 8.3 shows a similar trend to Chart 8.2 – costs increase as the length of pit-emptying cycle decreases. The sensitivity to the change in pit-emptying cycle length is higher than in the previous case, where the frequency of pit-emptying was allowed to vary. For a fixed frequency of pit-emptying, it is therefore more cost-effective to employ fewer pit-emptying teams for longer.

8.2.2.3 Frequency of emptying: fixed length of pit-emptying cycle, variable time between pit-emptying cycles

In this analysis, the length of the pit-emptying cycle was fixed at five years, and the time between pit-emptying cycles varied between zero and four years. The total costs per pit were calculated over a 9-year period, to enable comparison between costs. This variable considers the relative costs of removing a small amount of sludge from pits more frequently, versus a large amount of sludge less often. Chart 8.4 shows the generally increasing costs with lower frequency of emptying, for all three methods.

The length of the pit-emptying cycle was decreased to a fixed three years and the same analysis re-run, with costs per pit calculated over a 7-year period. Chart 8.5 again shows generally increasing costs with a lower frequency of emptying, but also shows a local maximum around a pit-emptying frequency of 5 years.

The shape of the curve is due to the combination of two effects:

- For decreasing frequency of emptying, emptying and transport costs rise as more sludge has to be handled per pit. This is shown by the bottom curve on Chart 8.4 and Chart 8.5.
- As frequency of pit-emptying decreases, the level of utilisation of the LaDePa and combustion plants varies non-linearly.

The additive effect produces the cost variations shown. In general, for either length of pit-emptying cycle, it is more cost-effective to follow cycles straight on from one another.

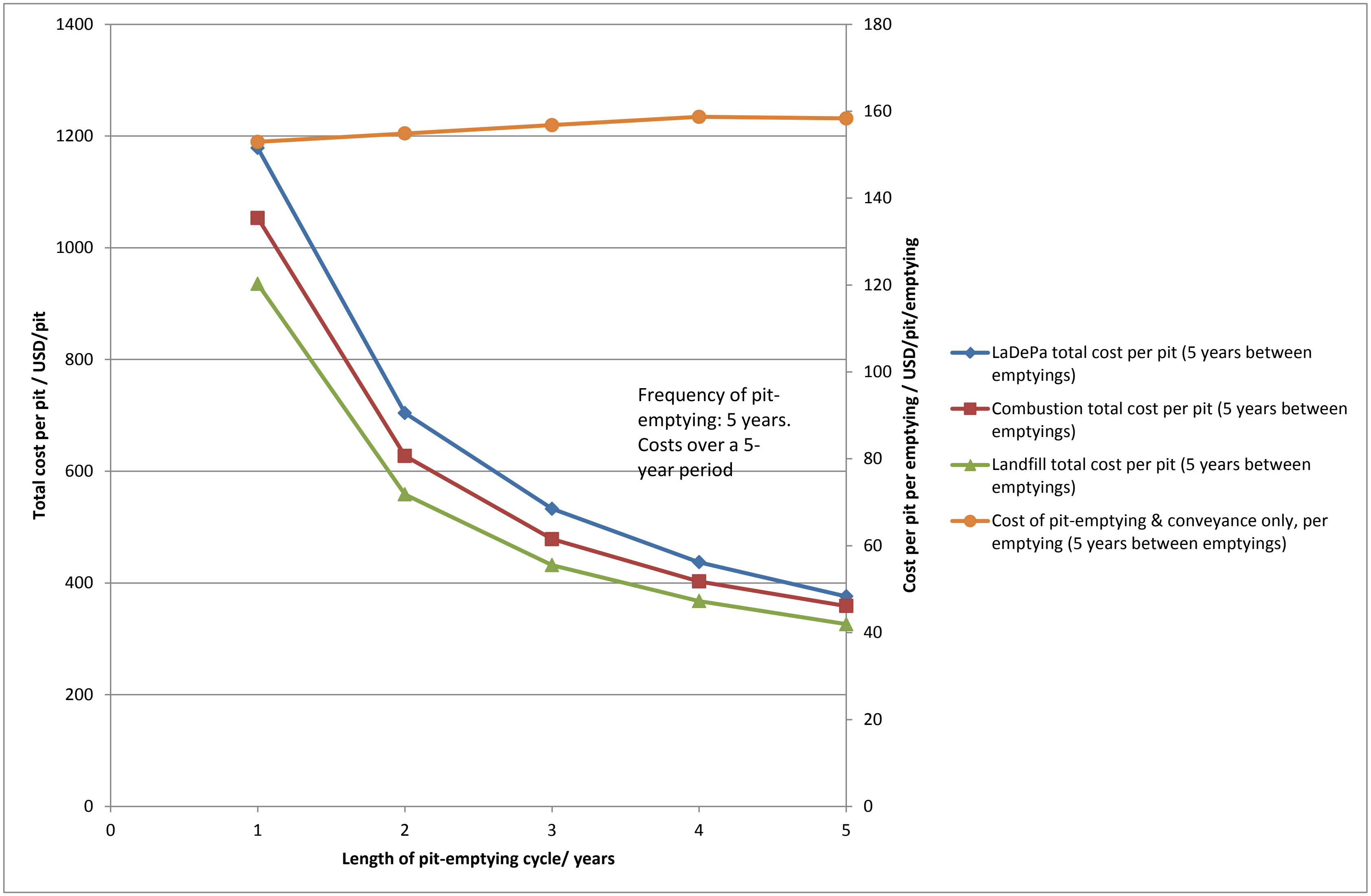

Chart 8.3: Variation in cost per pit with the length of pit-emptying cycle (fixed frequency of pit-emptying)

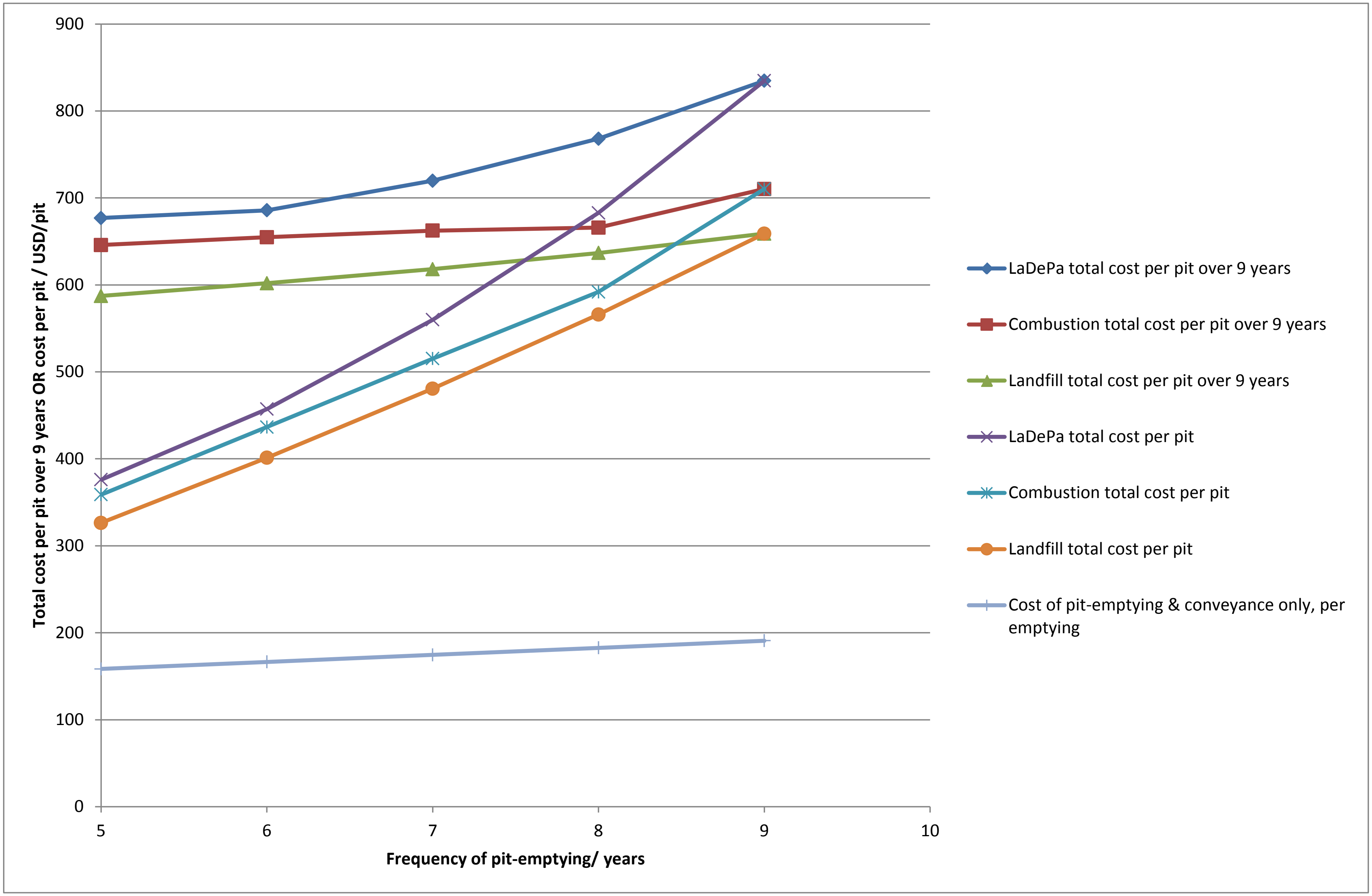

Chart 8.4; Variation in cost per pit with frequency of pit-emptying (5-year pit-emptying cycle)

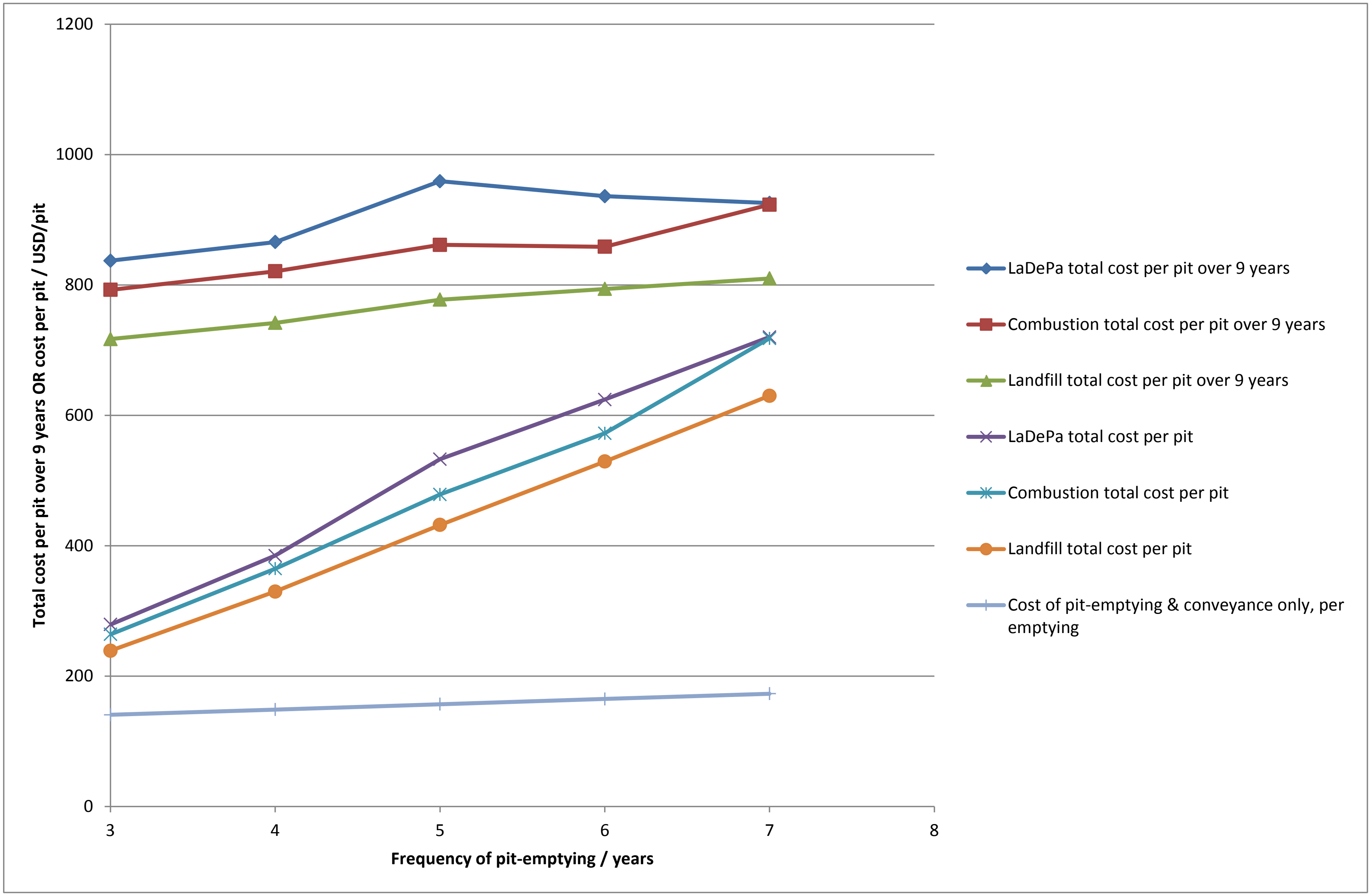

Chart 8.5: Variation in costs per pit with frequency of pit-emptying (3-year pit-emptying cycle)

8.2.2.4 Summary

The general conclusions from this analysis for structuring a pit-emptying programme are:

- For a fixed frequency of pit-emptying, the longer the pit-emptying cycle the lower the costs.
- For a variable frequency of pit-emptying, a 5-year pit-emptying cycle was shown to be lower-cost than a 3-year cycle.
- Where the pit-emptying cycle length is the same as the frequency of pit-emptying, then at cycle lengths over 3 years, costs become less sensitive to further increases in emptying-cycle length. This indicates that pits should not be emptied more than once every three years.
- For a fixed length of pit-emptying cycle, it is more cost-effective to follow cycles straight on from one another (as resources are more efficiently used, not being used in a stop-start manner).

8.2.3 Sludge dry solids and sludge accumulation rate in pits

The sensitivity of overall costs to variations in sludge dry solids and sludge accumulation rate in the pit is complicated, as the two variables are usually not independent of each other. Where the majority of sludge solids are retained in the pit, but there is water movement in and out of the pit, the sludge accumulation rate and sludge dry solids content will both vary. The following scenarios are possible:

(1) Sludge dry solids content varies in proportion to accumulation rate, maintaining a constant total dry mass of solids in the pit. This would be expected where there is only water movement in and out of the pit (e.g. groundwater ingress, or sludge water leaching out of the pit) but little movement of solids;
(2) Sludge accumulation rate varies whilst sludge dry solids remains constant. This is possible where entire portions of the pit's contents are being lost – e.g. overflow of sludge from the pit during wet seasons.
(3) Sludge dry solids content varies whilst sludge accumulation rate remains constant. If a constant volume of water is lost or added to the pit, but the number of pit users varies, the dry solids may fluctuate whilst the volume accumulation rate remains constant.

8.2.3.1 Variable sludge dry solids content and sludge accumulation rate

Initially, the sludge accumulation rate was varied in the model whilst keeping the total mass of dry solids in the pit constant, i.e. the sludge dry solids content was varied in proportion to the sludge accumulation rate. The base case of 40 ℓ/person/year and 30%DS in the pit was used to calculate the total mass of solids in the pit.

The shapes of the curves in Chart 8.6 are influenced by the limits on the feed dry solids that both the LaDePa and combustion processes can accept. These were set to:

- LaDePa minimum feed dry solids: 20%
- LaDePa maximum feed dry solids: 40%
- Combustion minimum feed dry solids: 20%
- Combustion maximum fee dry solids: 95%

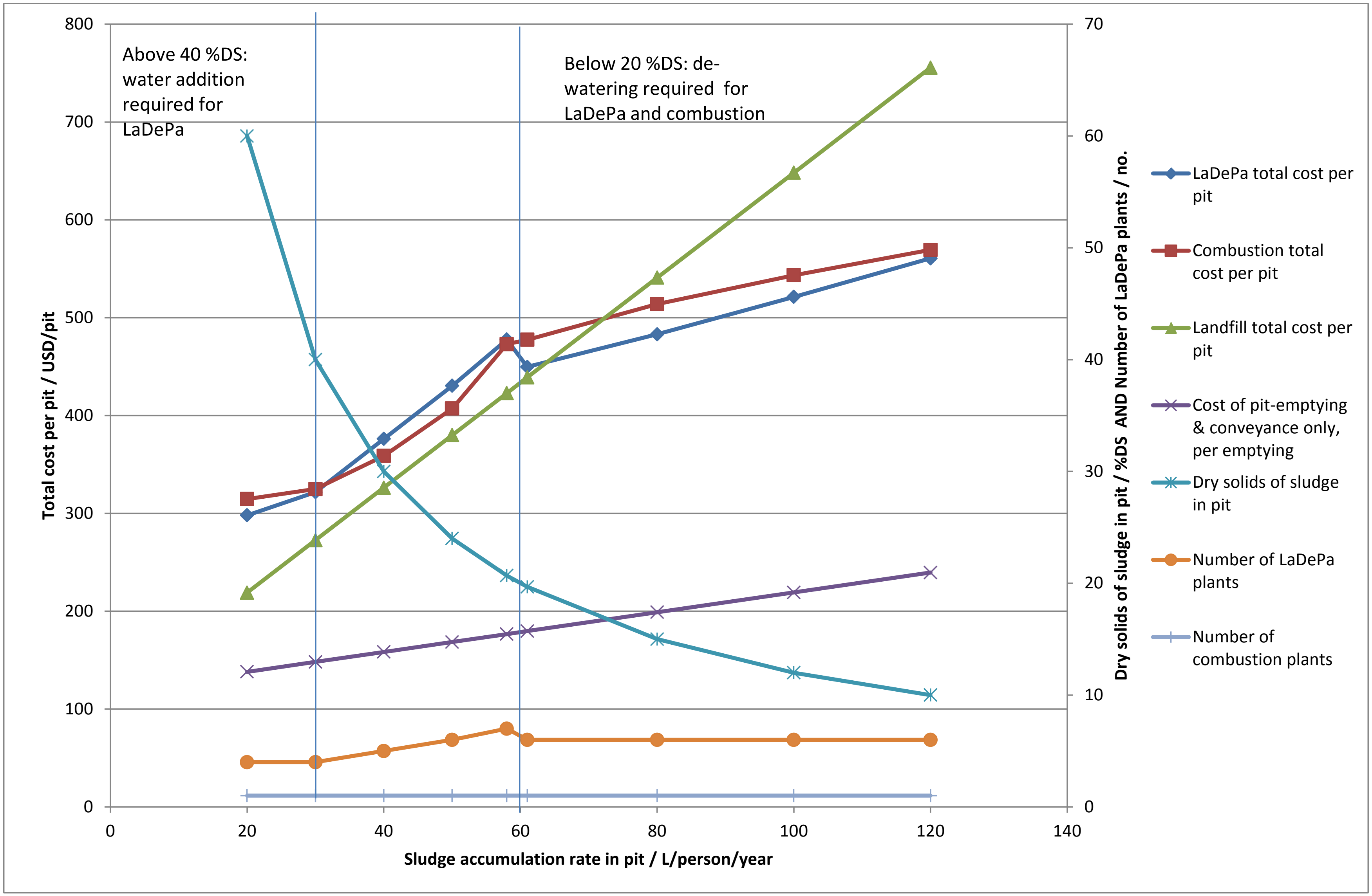

Chart 8.6: Variation in costs per pit with sludge accumulation rate (constant total mass of solids in the pit)

Below the minimum feed dry solids, sludge drying was required during pre-treatment and implied additional costs for both LaDePa and combustion. Above the maximum feed dry solids, water addition and mixing was required to produce an appropriate feed sludge, with additional associated costs.

The 20%DS and 40 %DS limits correspond to sludge accumulation rates of 60 and 30 ℓ/person/year respectively. These boundaries are indicated by the vertical lines on Chart 8.6. Below 20 %DS (above 60 ℓ/person/year), sludge will be dried to 20%DS before being fed to LaDePa or combustion, therefore the volumetric and mass feed rates are constant below this boundary, and the number of LaDePa or combustion plants required is also constant. The same logic applies above 40%DS (below 30 ℓ/person/year) for LaDePa, where sludge is watered down to 40% before being fed to the process.

Therefore for LaDePa, below 20%DS (above 60 ℓ/person/year) and above 40%DS (below 30 ℓ/person/year) the total cost of sludge disposal per pit increases with increasing sludge accumulation rate due to increased emptying and transport costs for the raw sludge and increased costs of sludge de-watering during pre-treatment. For combustion this is also true below 20 %DS (above 60 ℓ/person/year).

The slight decrease in the number of LaDePa plants required at just above 60 ℓ/person/year can be explained as follows: the feed rate of 60 ℓ/person/year exactly equals the volumetric capacity of 7 LaDePa plants. At accumulation rates above 60 ℓ/person/year, dewatering is required. Where dewatering takes place, so does removal of detritus prior to reaching the LaDePa plant. Therefore the total volumetric feed rate to the LaDePa plant at accumulation rates just above 60 ℓ/person/year is significantly lower than for slightly lower sludge accumulation rates (which correspond to sludge dry solids contents where dewatering is not required). The number of LaDePa plants therefore drops, and brings the total cost per pit down also.

Where no pre-treatment to remove or add water is required for LaDePa (between 30 and 60 ℓ/person/year), volumetric feed rate to LaDePa rises, and cost rises at a greater rate due to increased capital investment required in plants.

Below 60 ℓ/person/year accumulation rate, the dry solids content of the feed to combustion varies, as no de-watering takes place. However, the lower the dry solids of the sludge received, the higher the supplemental fuel requirements, causing the increasing gradient of the cost curve between 20 and 60 ℓ/person/year accumulation rates (60 to 20%DS respectively).

The costs of all three disposal routes exhibited high sensitivity to changes in sludge accumulation rate, with landfill the most sensitive (SI_N of 0.85). This is logical, as the capacity required for each disposal route is directly tied to sludge accumulation rate.

8.2.3.2 Variable sludge dry solids content; constant sludge accumulation rate

Results of varying sludge dry solids content, whilst maintaining a constant sludge accumulation rate (40 ℓ/person/year), are shown in Chart 8.7. Within the acceptable feed dry solids range, the cost per pit for LaDePa does not vary, as plant capacity is based on volumetric feed rate. The cost of production per tonne of LaDePa pellets does vary.

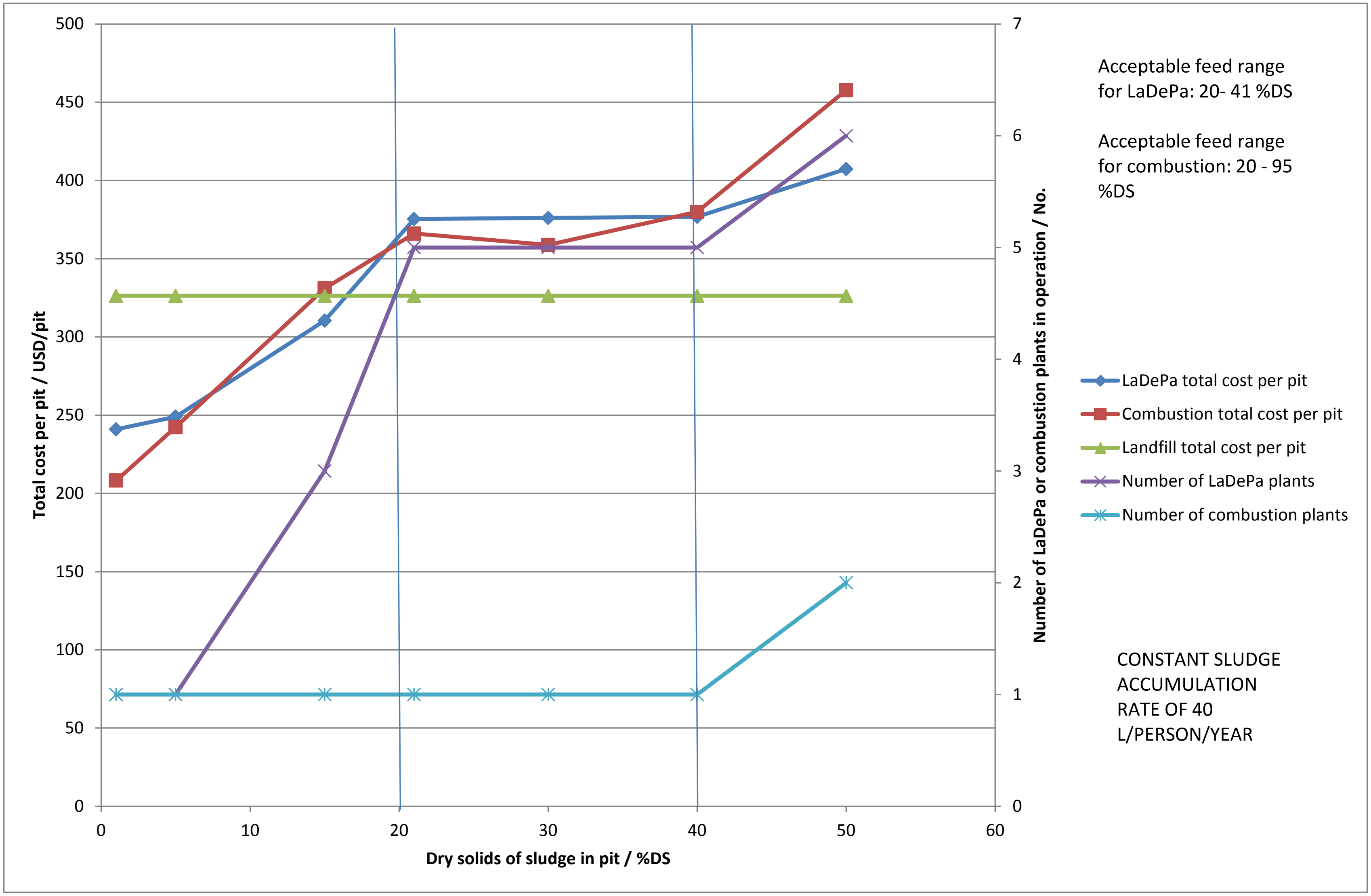

Chart 8.7: Variation in cost per pit with dry solids content of sludge (constant sludge accumulation rate)

Below the acceptable minimum feed dry solids, dewatering is required and the feed volume to LaDePa decreases, with a corresponding decrease in the number of LaDePa plants required and the cost per pit. However, dewatering costs increase as the dry solids drop, and the result of the two competing effects means the rate of increase in costs is not constant.

Above the maximum feed dry solids, water must be added to the sludge before feeding to the LaDePa plant. This implies additional costs for the water addition and mixing facility, and for the greater number of plants required to process the additional feed volume.

Combustion capacity is based on a dry solids feed rate, therefore the higher the dry solids content of the sludge, the higher the incineration capacity required. Below 20%DS, sludge must be dewatered up to the 20%DS minimum feed requirement. The lower the initial dry solids, the higher the dewatering costs. However, lower combustion capacity (and therefore supplementary fuel quantity) is required for lower dry solids sludge. This cost dominates over drying costs, resulting in lower combustion costs per pit for lower dry solids content sludge.

Above 20 %DS, no dewatering costs apply. As sludge dry solids content increases, a greater total mass of solids is fed to combustion, and thus a higher combustion capacity is required. However, the supplemental fuel requirement **per kg** of wet sludge feed decreases as sludge dry solids content increases. The two competing effects are seen in the concave shape of the combustion cost curve above 20 %DS. Initially, the higher fuel cost per unit wet mass of feed sludge dominates the overall cost per pit. At approximately 30 %DS, the costs of additional plant capacity take over, and the curve reverses direction.

The sensitivity of costs per pit to sludge dry solids content only is lower than the sensitivity to dry solids content when varied in proportion to sludge accumulation rate. The cost of combustion was the most sensitive to changes (SI_N of 0.56). The SI_N for landfill was 0, because no density variation was allowed for when dry solids content was changed.

8.2.3.3 Variable sludge accumulation rate; constant sludge dry solids

For this analysis, sludge dry solids was set at 30 %DS. Chart 8.8 shows that the costs per pit are directly related to the number of LaDePa and combustion plants required. Discontinuities are seen in the cost curves where the number of plants required increases.

8.2.3.4 Summary

The general conclusions from a cost-per-pit perspective are:

- Lower sludge accumulation rates result in lower costs per pit, regardless of the relationship of sludge accumulation with dry solids.
- Combustion is far more sensitive to changes in sludge accumulation rate than LaDePa or landfill, when sludge dry solids vary in proportion to accumulation rate.
- When sludge accumulation rate varies independently of dry solids content, costs for all three methods show approximately the same sensitivity to changes in accumulation rate.
- For a fixed sludge accumulation rate of 40 ℓ/person/year, lower dry solids generally result in lower costs per pit for LaDePa, despite the additional costs incurred from sludge pre-drying.
- For combustion, costs per pit also generally rise with increasing sludge dry solids. However, a local maximum in costs is seen near to the minimum acceptable dry solids limit for feed to combustion.
- Landfill costs are unaffected by changes to sludge dry solids content, assuming density remains constant.

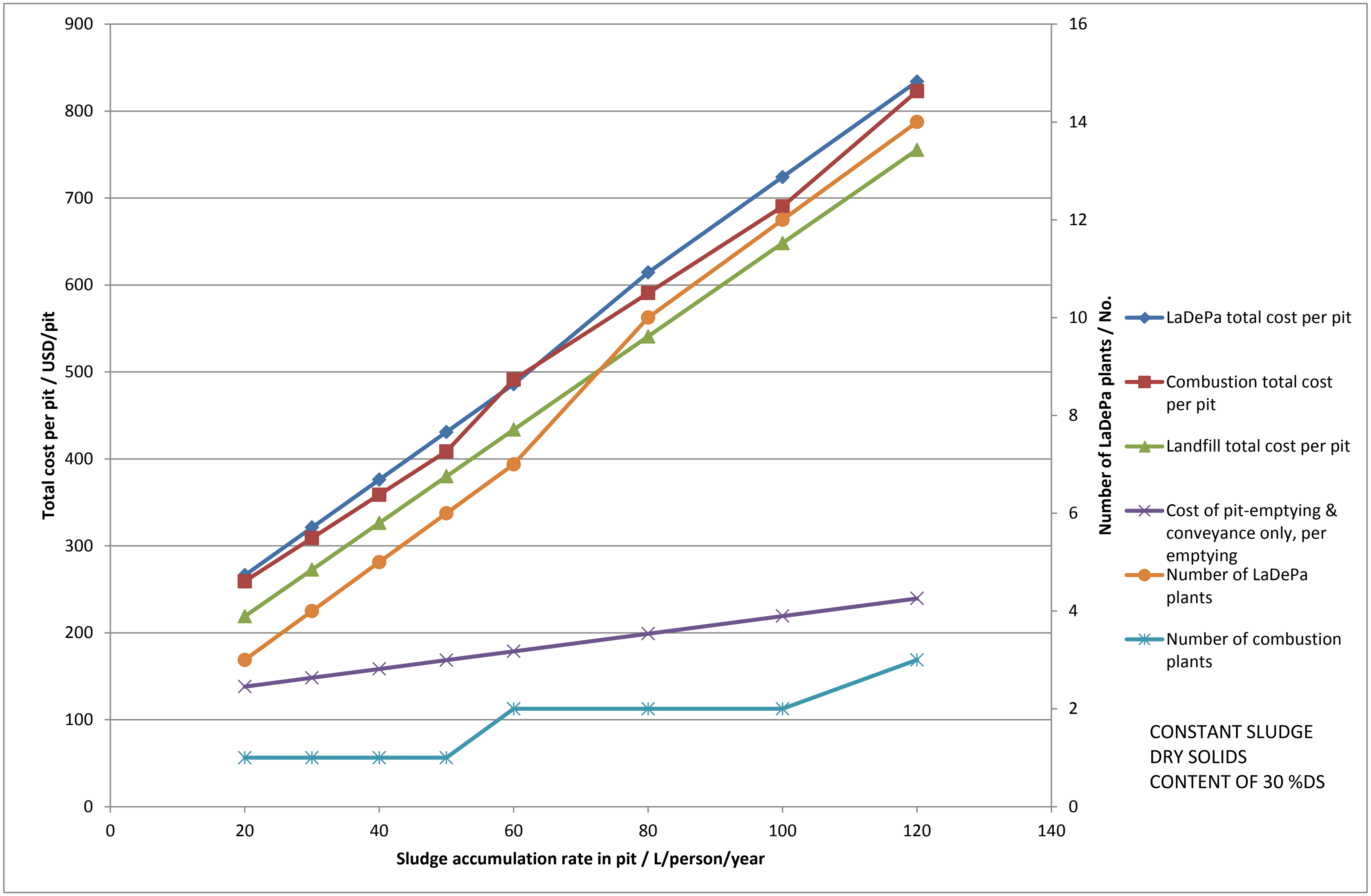

Chart 8.8: Variation in cost per pit with sludge accumulation rate (constant sludge dry solids content)

8.2.4 Detritus content of sludge in pits

Maximum allowable detritus content in the feed to LaDePa was set at 40%. Detritus is removed manually as sludge enters the hopper to the screw feed, or is separated by the screw-extruder system. Maximum allowable detritus content in the feed to combustion was set at 50%. This limit is difficult to define as it will be system-specific and dependent on the type of detritus present in the sludge (its calorific value and ease of feeding to the combustion system).

A detritus range of 0 – 40 vol% was considered for this analysis. Within this range, the costs of combustion and landfill do not vary. Cost of LaDePa increases with detritus volume due to increasing landfill costs for the separated detritus. The sensitivity of the LaDePa cost to detritus content was not as significant as for most other parameters (SI_N of 0.18). At detritus contents under 10%, the LaDePa process is predicted to be more cost-effective than combustion. Better solid waste collection services could therefore make LaDePa the more economically viable option. Chart 8.9 summarises the results.

8.2.5 Wet sludge density

The density of wet VIP sludge has been measured by Zuma et al (2013) as between 740 and 2 160 kg/m3 with an average of 1 400 kg/m3 (from 96 samples). The density chosen for the model base case was 1 150 kg/m3 with a dry solids content of 30 %DS. At 30 %DS, if all solids were dissolved the expected density would be approximately 1 430 kg/m3 (assuming no significant volume change on dissolution). As a considerable portion of solids were known to be suspended the lower density value of 1 150 kg/m3 was chosen. Density was varied in the range 900 kg/m3 to 1 300 kg/m3, keeping the dry solids content of the sludge at a fixed 30 %DS. The results are given in Chart 8.10.

The results showed that the cost per pit for the LaDePa process does not vary with density, as the LaDePa plant capacity is determined by volumetric flowrate, not dry mass. Cost per pit for combustion and landfill are density-dependent as capacity is dependent on the solids mass in the sludge. Sensitivity of costs to changes in density was medium for both combustion and landfill (SI_N of 0.47 and 0.57 respectively). At density values over approximately 1280 kg/m3 combustion becomes more expensive than the LaDePa process. The cost per tonne of producing LaDePa pellets or combustion ash logically decreases with increasing density of wet sludge. It is unlikely that changes to density would make landfill more expensive than LaDePa, as average density of sludge would have to be over approximately 1450 kg/m3.

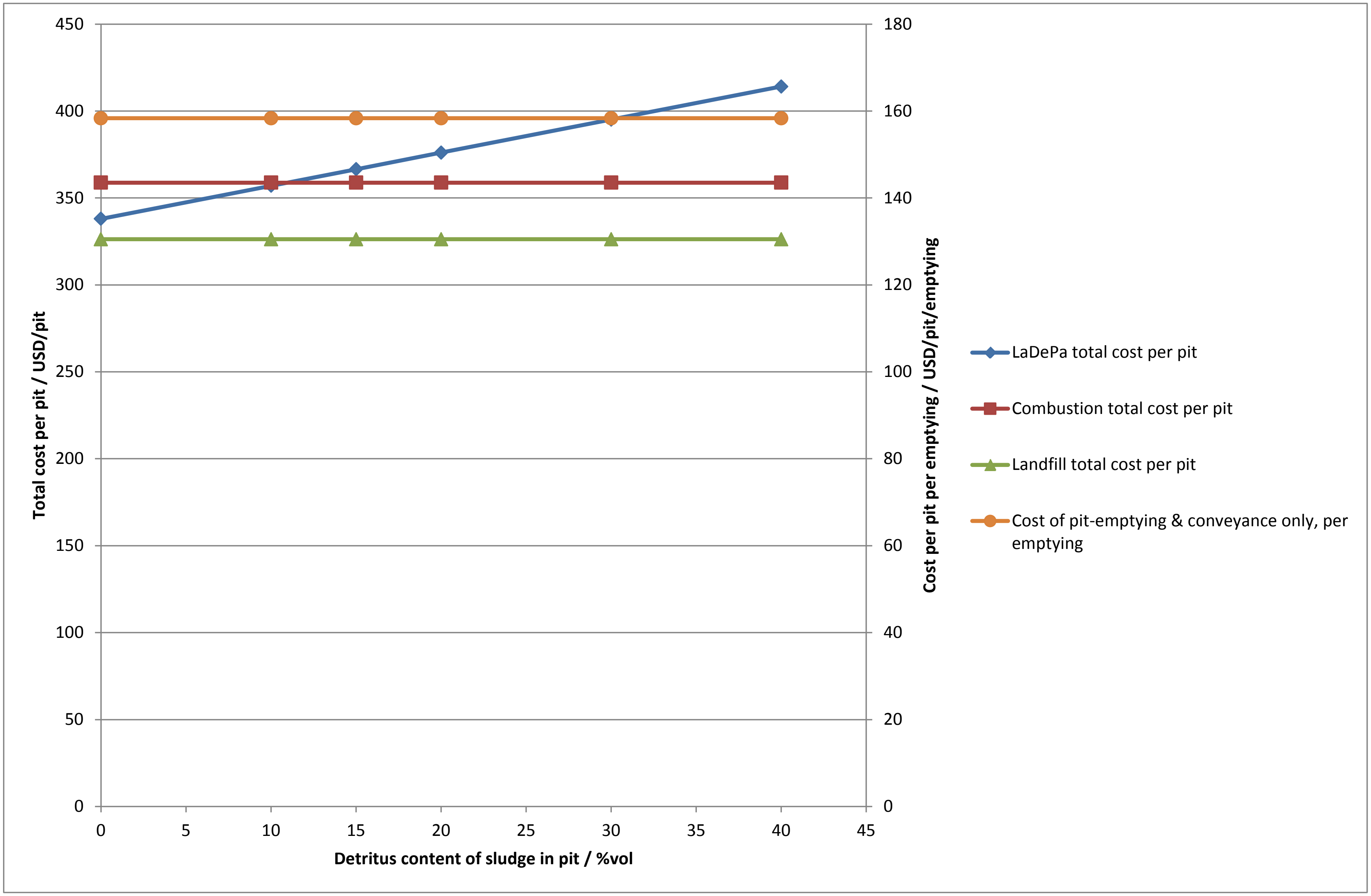

Chart 8.9: Variation in cost per pit with sludge detritus content

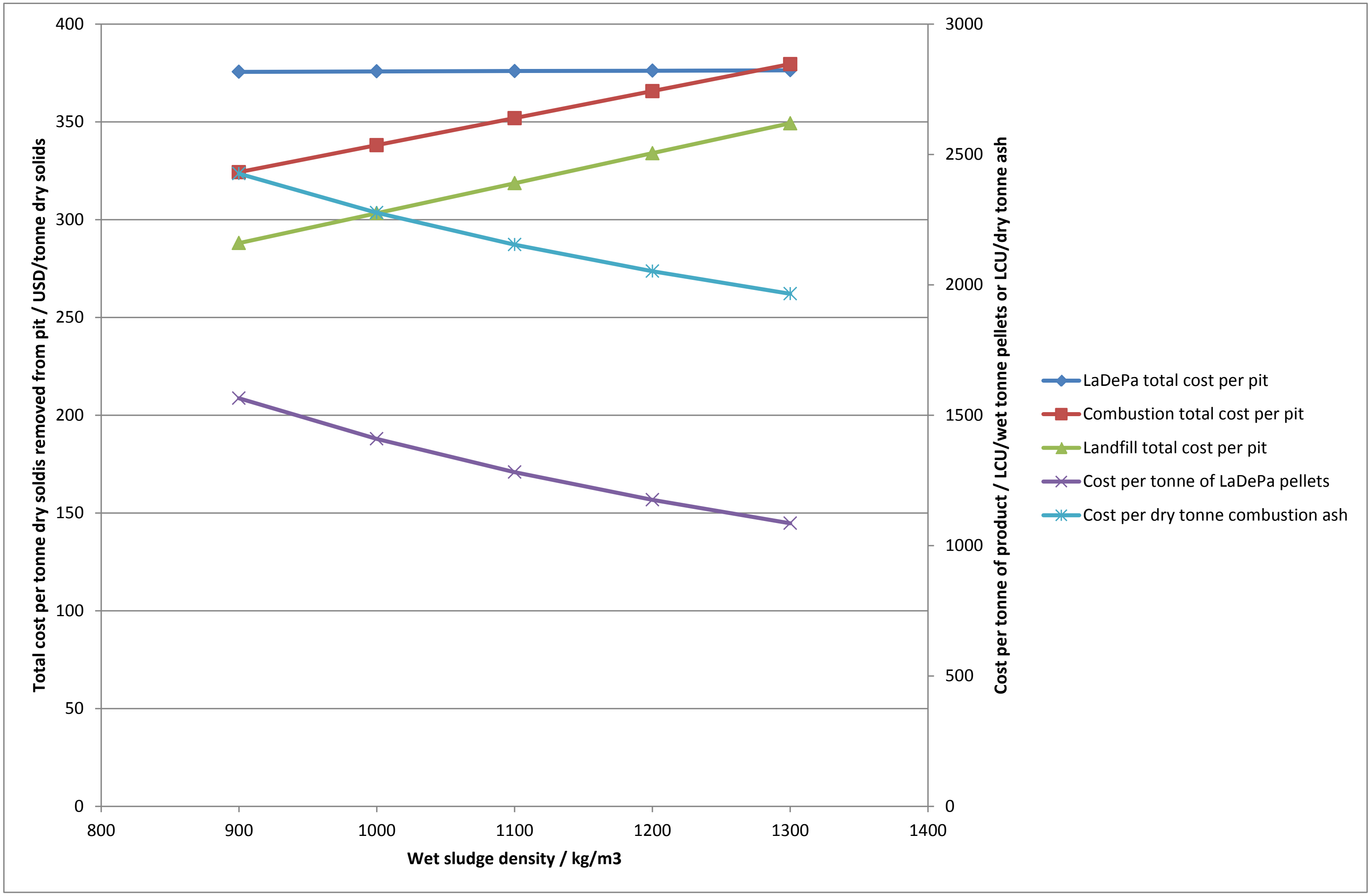

Chart 8.10: Variation in cost per tonne of dry solids removed with density of wet sludge

8.2.6 Travel distances

8.2.6.1 Distance T1: from pit to LaDePa or combustion plant site

The costs of all three disposal routes vary linearly with the distance from the pit to the disposal site. An increase in distance from 2 to 25 km (SI_I of 0.92) gives an approximately 25% rise in total costs for all three disposal routes, with SI_D values in the range 0.19 to 0.20. The SI_N values were therefore between 0.21 and 0.22 for all disposal methods – i.e. a significant but lower sensitivity in comparison with some of the other variables. The cost of pit-emptying and conveyance by itself rises by 62% (SI_D of 0.38, SI_N of 0.41). The results are given in Chart 8.11.

This chart can also be used to consider the effect of having several decentralised LaDePa plants and only one centralised combustion plant. The model base case assumed the same average distance from the pit to a LaDePa plant as from any pit to the combustion plant, even with several different LaDePa plants. With decentralised LaDePa plants, the average distance from the pit to the LaDePa plant would probably be lower than from the pit to the combustion site or to the landfill site. If the average distance to the combustion plant was 25km, the distance to the landfill site was also 25km and the distance to the LaDePa plant was 5km, the costs per pit would be as follows:

LaDePa cost per pit:	350 USD/pit
Combustion cost per pit:	403 USD/pit
Landfill cost per pit:	368 USD/pit

It is reasonable to assume that LaDePa plants would be easier to decentralise, and to make into mobile plants, than incineration plants. This result is key in showing how decentralisation could make LaDePa more economically viable than combustion or landfill.

It can therefore be concluded that:

- Costs of all disposal routes vary linearly with distance from pit to disposal site.
- Good decentralisation of LaDePa plants could make LaDePa a cheaper option than both combustion and landfill.

8.2.6.2 Distance E1: from pit to sub-contractors base

Costs of all three disposal routes again vary linearly with distance from the pit to the sub-contractor's base, but are less sensitive to this variable than the distance from pit to sludge processing site. An increase in distance from 2 to 25 km (SI_I of 0.92) gives approximately 11% rises in total costs for the three disposal routes (SI_D values in the range 0.09 to 0.10). The SI_N values were therefore between 0.10 and 0.11 for all disposal methods. The journey from the sub-contractor's base is assumed to only occur once per day, as opposed to the multiple journeys required to the LaDePa or combustion site to dump sludge. Results are shown in Chart 8.12. It is unlikely that this distance would vary between the three disposal methods.

8.2.6.3 Summary

The cost of all three disposal methods increases linearly with increasing distance between the pit and the sub-contractor's base. Costs are less sensitive to this distance than to the distance between pit and disposal site. This result shows the level of advantage to be gained from using pit-emptying sub-contractors that are local to the pit-emptying area.

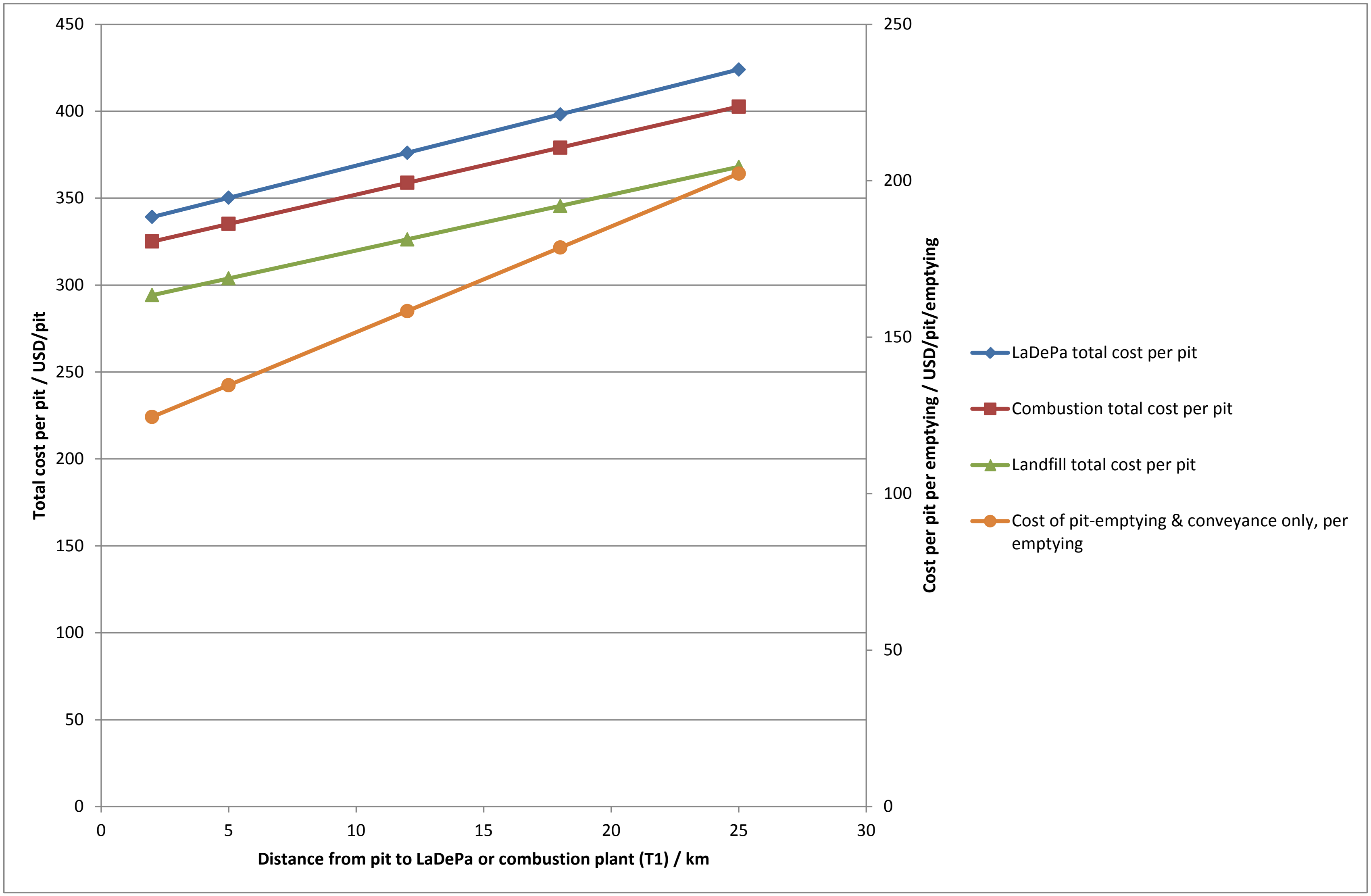

Chart 8.11: Variation in cost per pit with distance from the pit to the sludge disposal site

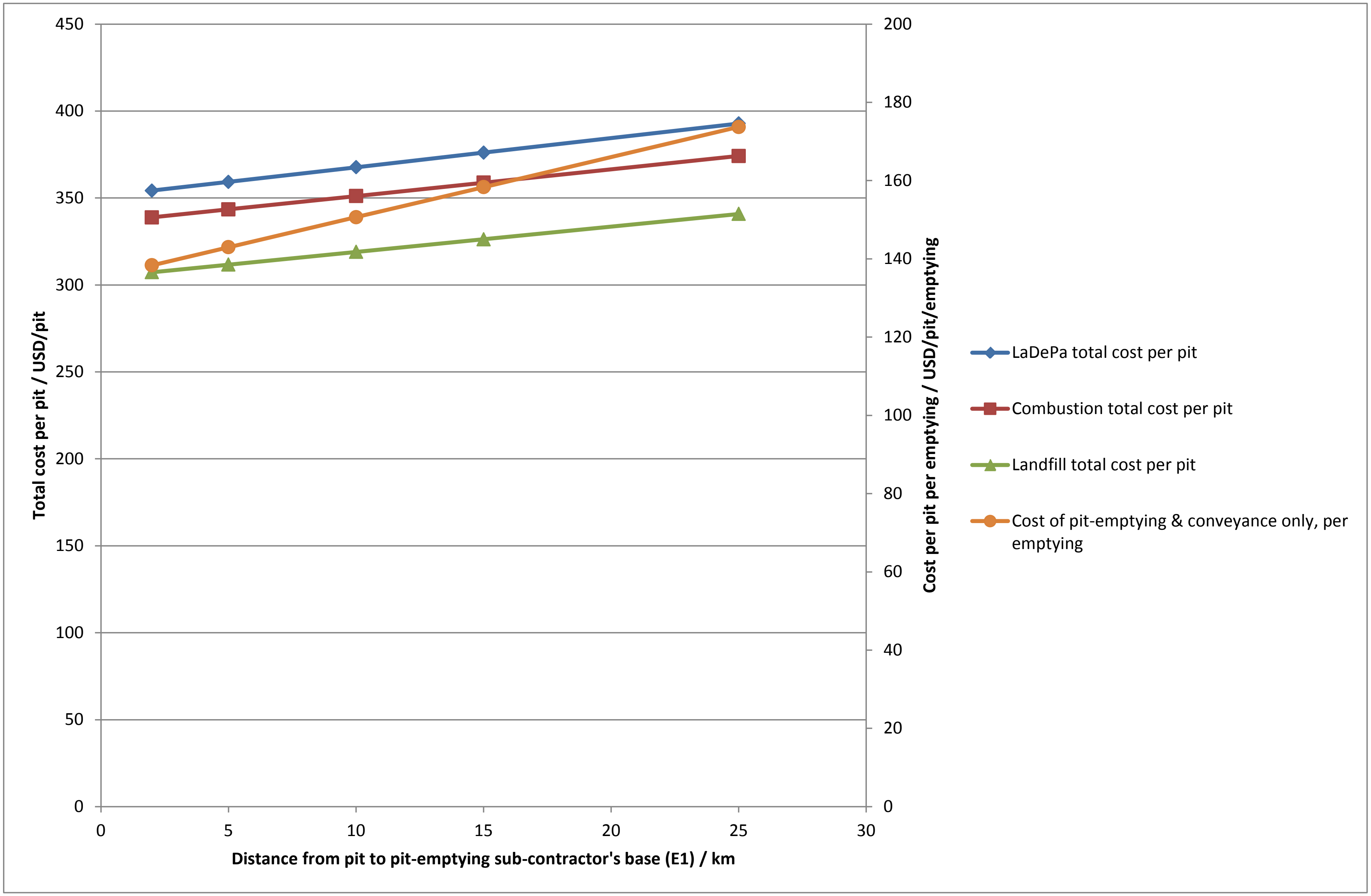

Chart 8.12: Variation in cost per pit with distance from the pit to the subcontractor's base

8.2.7 Pit-emptying sub-contractor mark-up

The pit-emptying sub-contractor mark-up rate is applied to the costs of emptying and conveyance only. An increase from 5 to 40% (SI_I of 0.88) gave total cost increases of approximately 22% for all the three disposal methods (SI_D of 0.18 for all methods). The SI_N of between 0.20 and 0.21 for all methods indicates a low-medium sensitivity of costs to this input. Results are given in Chart 8.13.

8.2.8 Main contractor mark-up rate

The main contractor mark-up rate is applied to the sum of the emptying and conveyance costs (including sub-contractor mark-up) and the operating and maintenance costs of sludge processing by LaDePa or combustion, excluding fuel costs. The mark-up rate was varied between 5 and 30% (SI_I of 0.92). Total cost per pit increased linearly with the mark-up rate, with LaDePa and combustion costs per pit increasing from 346 to 421 USD/pit and 333 to 397 USD/pit respectively (SI_D values of 0.18 and 0.16). Cost of landfill was not affected as no managing contractor is used to manage this disposal route. The sensitivity of the LaDePa and landfill costs to this mark-up rate was approximately the same as the sensitivity to the pit-emptying sub-contractor's mark-up rate (SI_N values of 0.21 and 0.19 respectively for the main contractor mark-up rate). Results are shown in Chart 8.14.

8.2.9 Inputs specific to the LaDePa disposal route

8.2.9.1 LaDePa annual lease rate and royalties

The LaDePa lease rate for the base case was set at 60 000 USD/year with additional royalties of 50 000 USD/year. These are guide values based on information from eThekwini Water and Sanitation, and are likely to vary depending on the structure of future contracts between the municipality and PSS, the company that owns and leases the LaDePa plants. It is therefore important to gauge the sensitivity of the overall costs to these inputs. The combined value for the lease and royalties was varied between 25 000 to 220,000 USD/year (SI_I of 0.89). The corresponding increase in LaDePa cost per pit was from 307 to 466 USD/pit (SI_D of 0.34). Sensitivity of LaDePa costs to the lease/royalties rate was medium, with an SI_N of 0.39. Results are shown in Chart 8.15

8.2.9.2 Minimum dry solids content of feed sludge to LaDePa

The LaDePa feed must have a minimum dry solids content in order for the process to function effectively. If sludge is too wet, it cannot be extruded into pellets that will hold their shape for drying. The minimum dry solids limit is yet to be determined during operation of the plant, therefore an estimated value of 20 %DS was used in the model base case. The limit defines when de-watering of sludge during pre-treatment is required.

Results are shown on Chart 8.16. Where the sludge dry solids content is above the minimum feed requirement, LaDePa costs do not vary, as there is no change in emptying and conveyance costs or required LaDePa capacity (as these are based on sludge volume, which does not change).

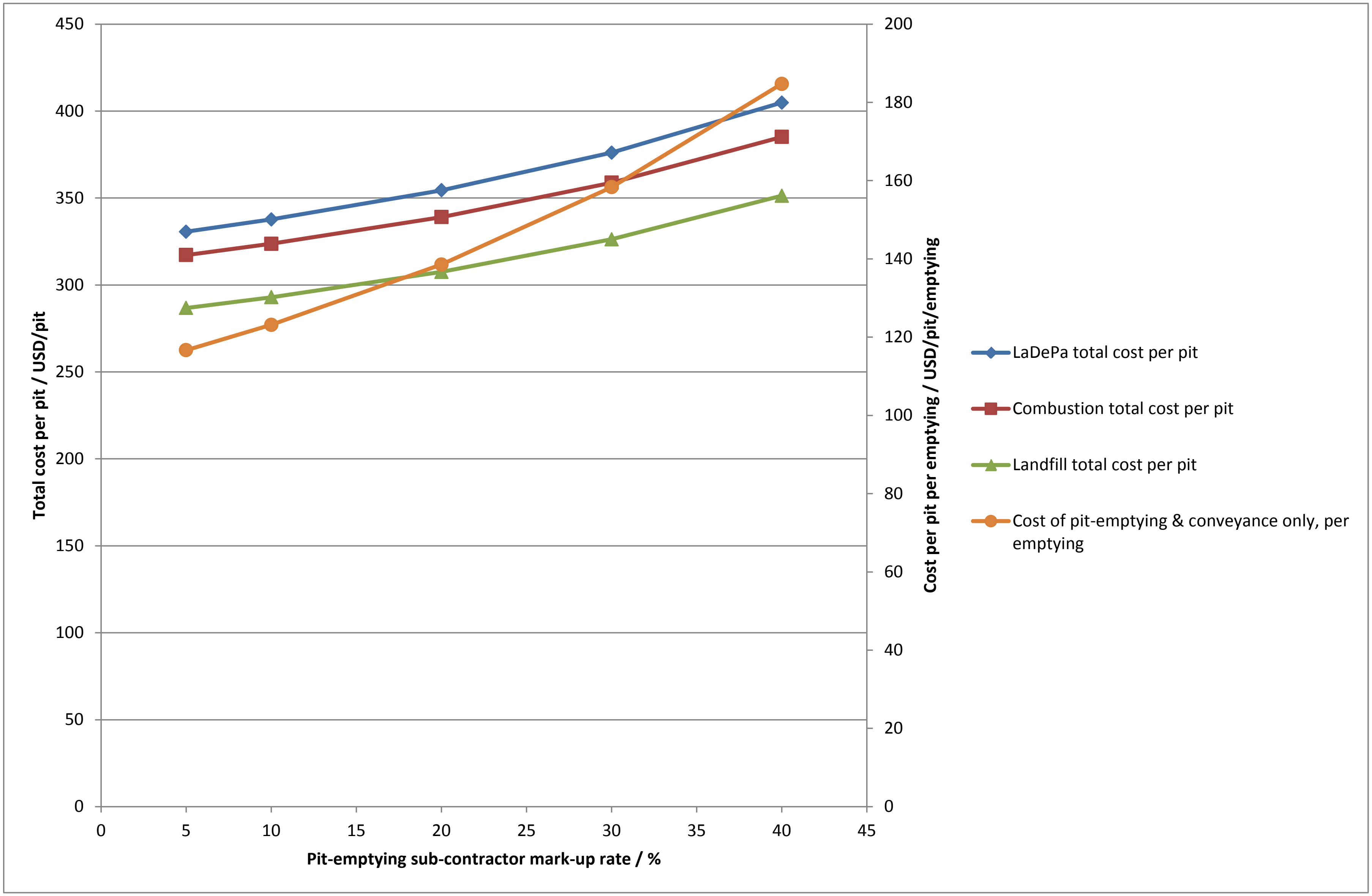

Chart 8.13: Variation in cost per pit with the pit-emptying subcontractor's mark-up rate

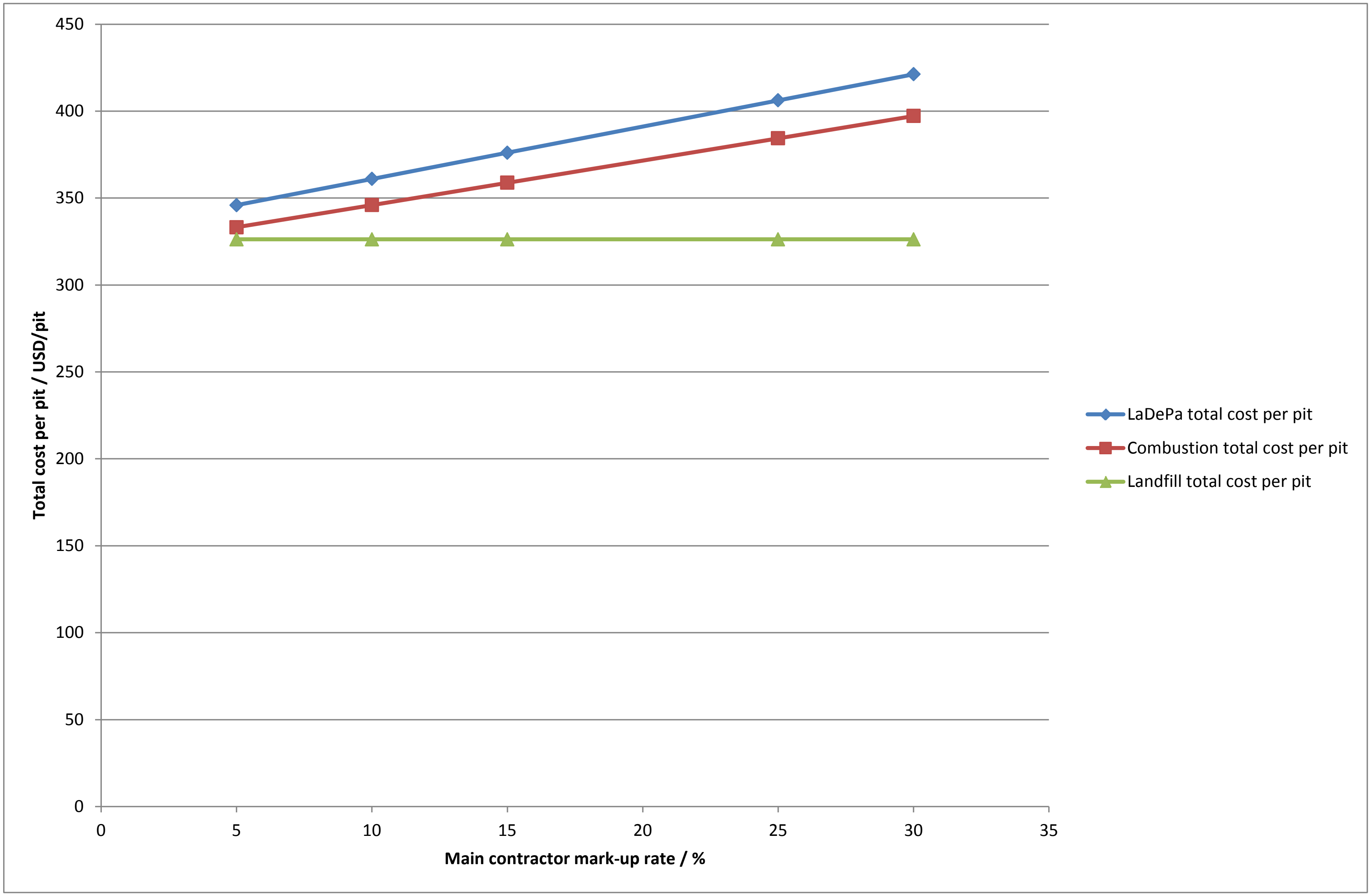

Chart 8.14: Variation in cost per pit with the main contractor mark-up rate

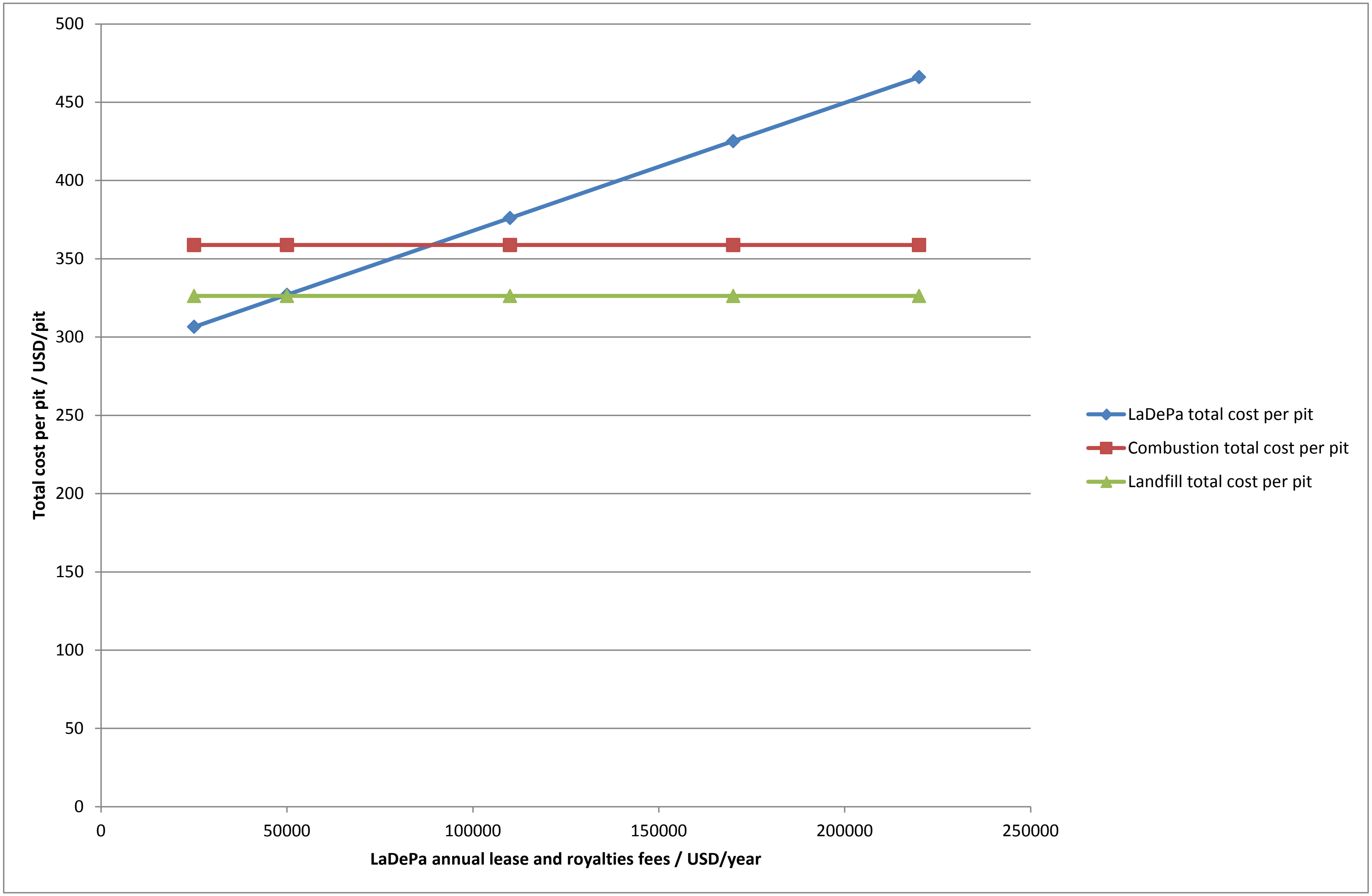

Chart 8.15: Variation in cost per pit with the LaDePa annual lease and royalties rate

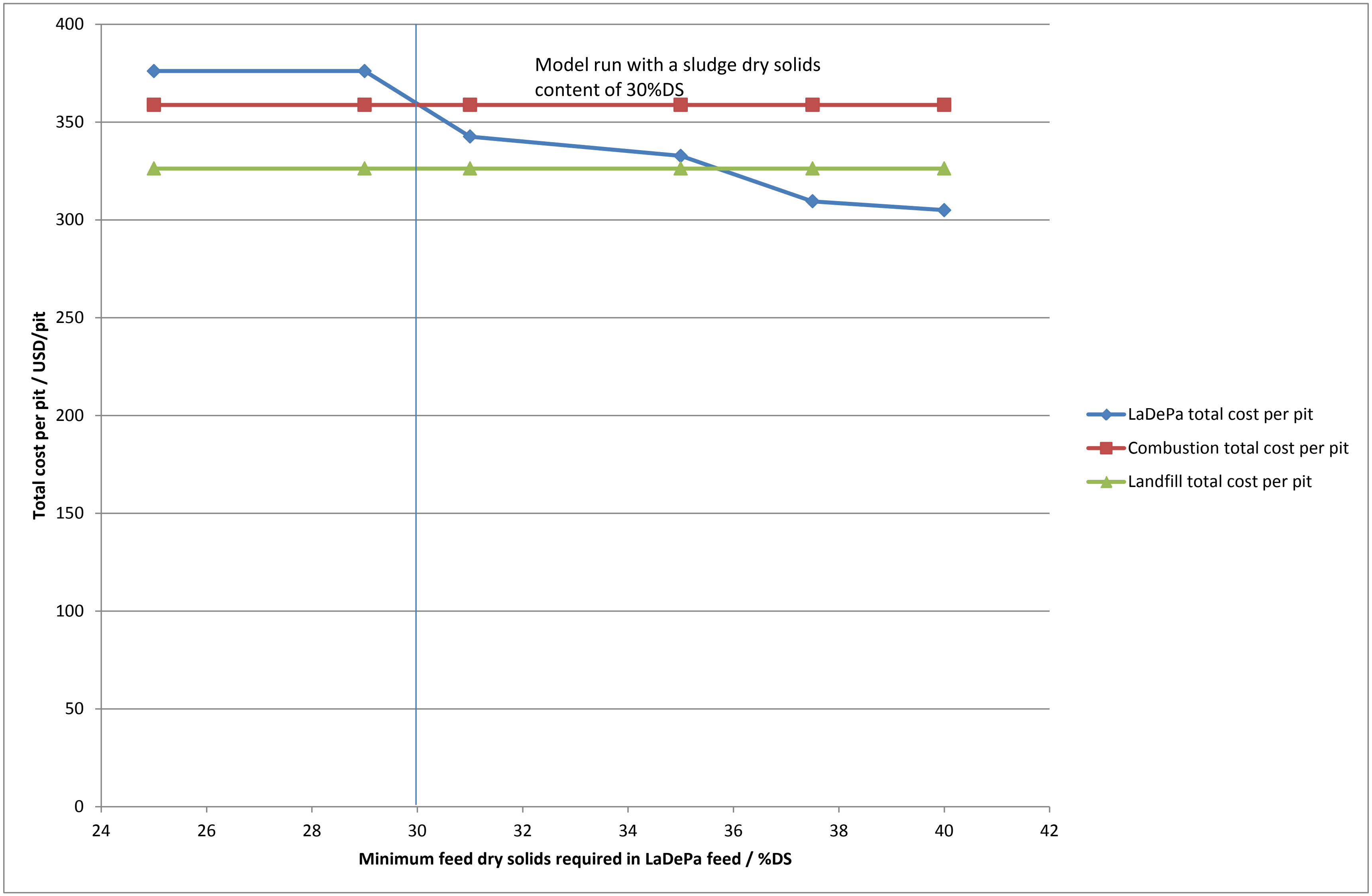

Chart 8.16: Variation in the cost per pit with the minimum feed dry solids accepted by the LaDePa process

Where the sludge dry solids content is under the minimum feed requirement, dewatering is required, implying higher costs. The further away the actual sludge dry solids is from the minimum required limit (i.e. moving right from the vertical line on the chart), the higher the costs of dewatering.

However, when sludge is dewatered detritus is also removed. This, together with the water lost from the sludge, reduces the plant capacity required to process the sludge and therefore lowers costs. For the drying costs entered into the model, the cost reduction due to lower plant capacity requirements has out-competes the effect of higher drying costs. Overall costs per pit drop as the minimum dry solids limit increases.

Chart 8.17 shows the same scenario run at higher drying costs. The higher costs of dewatering are reflected in the cost curve down to approximately 34 %DS. The dip in the cost curve between 30 %DS (the same as the dry solids of the sludge) and 34 %DS minimum feed requirement can be explained as follows: When LaDePa feed sludge is dewatered, detritus is also removed, reducing the plant capacity required to process the sludge (and therefore overall cost). Just above the feed sludge dry solids limit, dewatering does not occur and detritus is not removed during pre-treatment, so a higher plant capacity is actually required than when sludge is just below the minimum feed requirement.

The relationship between cost and the minimum feed solids that can be accepted by the LaDePa plant is dependent on the costs of drying the sludge. For sludge that falls just below the feed limit, costs may be lower because detritus will have been removed during the pre-treatment to dry the sludge. The sensitivity of LaDePa costs to this variable are high (SI_N of 0.5), highlighting the importance of determining what this limit is through operational testing on the LaDePa plant in order to extract more accurate costings from the model.

8.2.9.3 Volumetric feed rate to LaDePa

The volumetric feed capacity of the LaDePa plant currently in operation in eThekwini municipality is estimated to be 6 m3/day, but this has not yet been confirmed through measurement. It is therefore important to understand how a variation in this parameter could affect costs.

As expected, the results show that the number of plants required varies in proportion to volumetric feed capacity per plant. The cost of LaDePa disposal therefore decreases as volumetric capacity per plant increases. The rate of cost decrease varies with different numbers of LaDePa plants in operation. Results are shown in Chart 8.18.

Sensitivity of LaDePa costs to the actual volumetric feed rate is significant, but not high compared to other inputs (SI_N of 0.48).

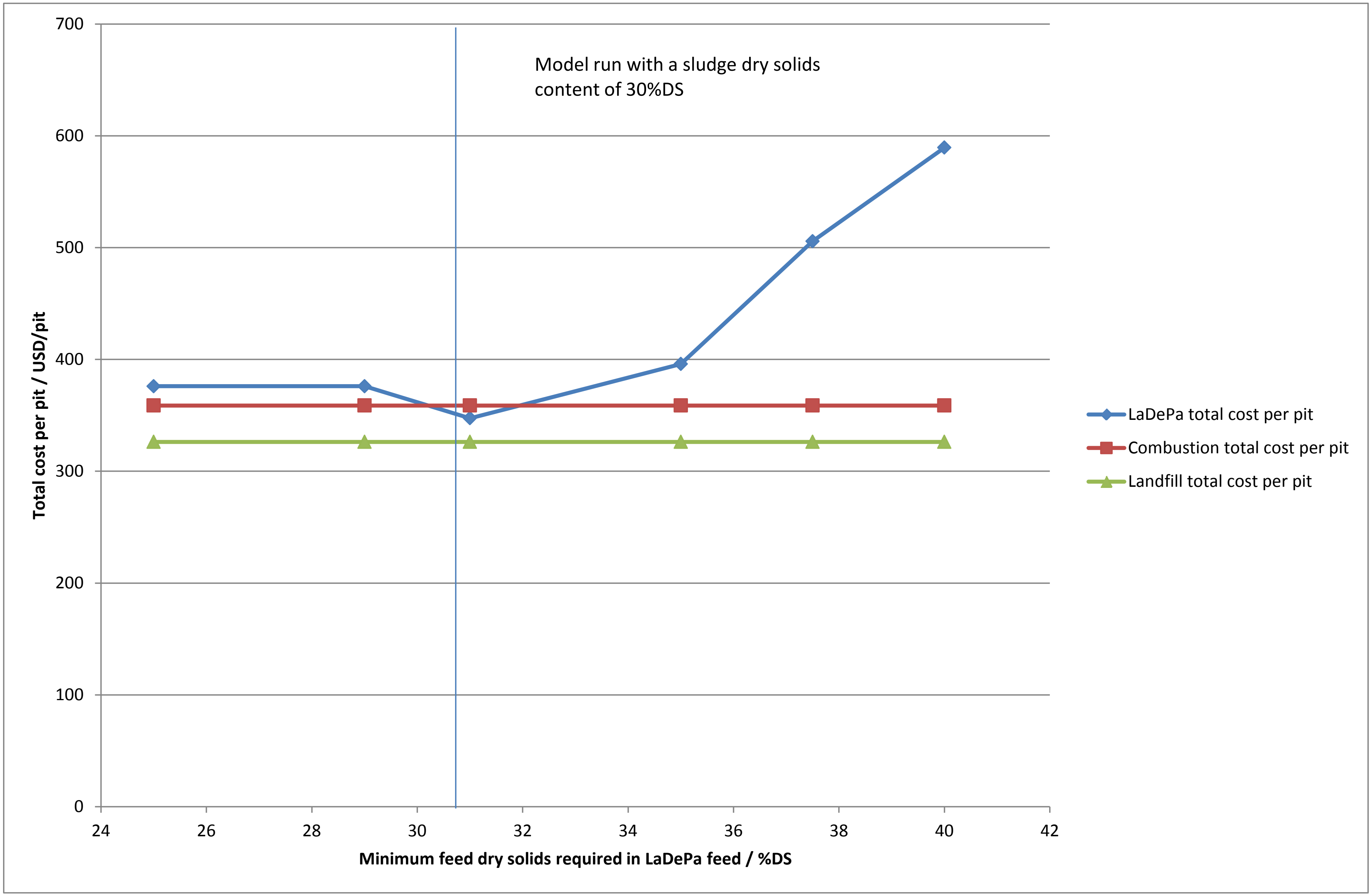

Chart 8.17: Variation in the cost per pit with the minimum dry solids required by the LaDePa process (higher sludge pre-drying costs)

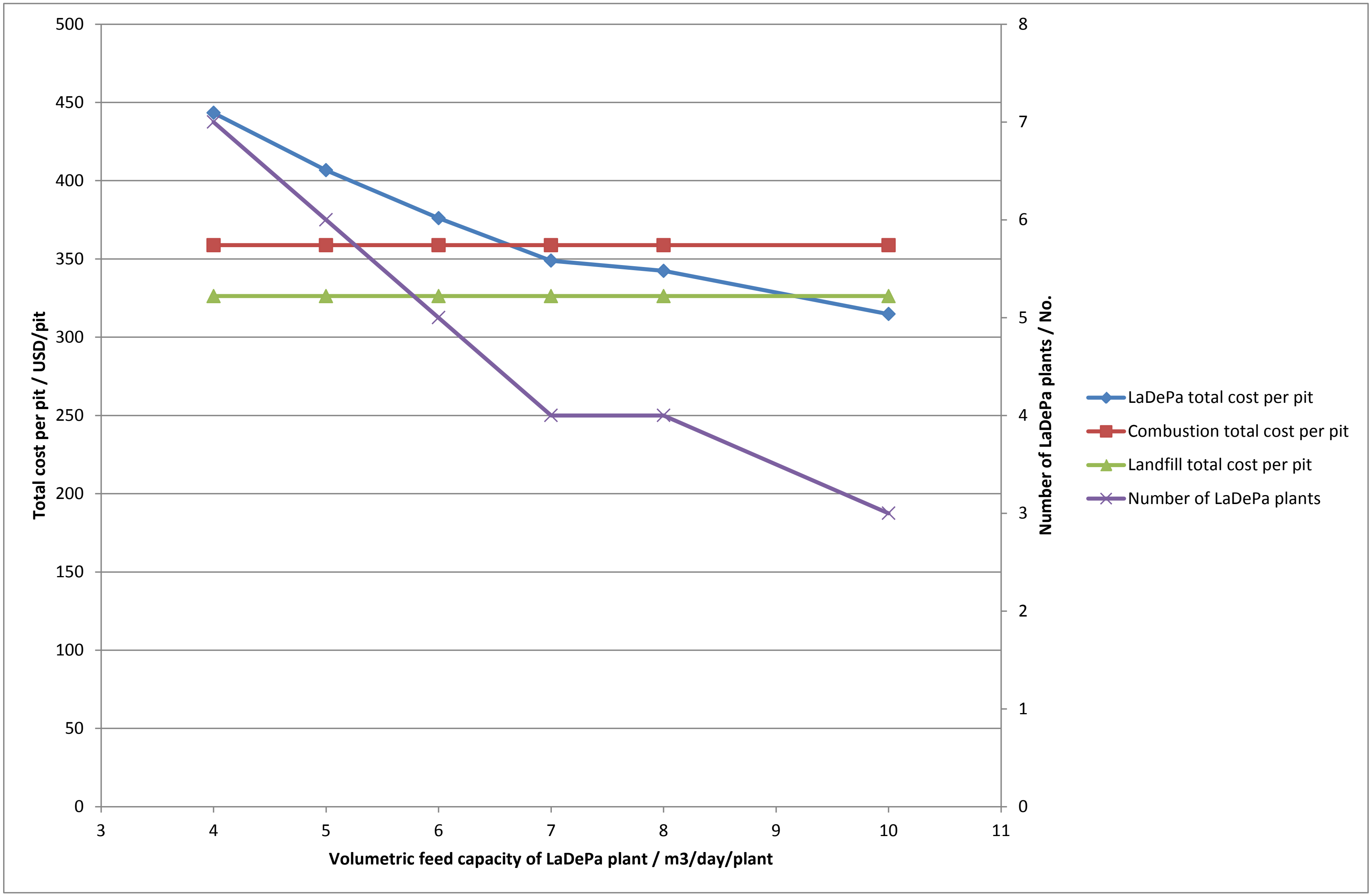

Chart 8.18: Variation of the cost per pit with the volumetric capacity of the LaDePa plant

8.2.10 Inputs specific to the combustion disposal route

8.2.10.1 Minimum dry solids content required in feed to combustion

The combustion process can accept a wide range of feed dry solids contents. For wetter sludge, more supplementary fuel is required to maintain the temperature of the incinerator. A minimum dry solids content for the combustion feed was included in the model, but its actual practical value is unknown. Where this is above the feed dry solids, dewatering pre-treatment is required, implying higher costs per pit. However, for a fixed sludge accumulation rate, the lower the dry solids of the sludge, the lower the combustion plant capacity required. These two effects compete, giving a local minimum in costs. Results are shown in Chart 8.19.

The sensitivity of combustion costs to this input is very low (SI_N of 0.04). As with the LaDePa, this will be dependent on the cost of pre-drying sludge.

8.2.10.2 Calorific value of sludge feed to combustion

Calorific value is given per unit mass of dry solids. At a constant dry solids content, the lower the calorific value of the feed, the higher the quantity of supplementary fuel required to maintain incinerator temperature and therefore the higher the costs per pit of disposal by combustion. Results are given in Chart 8.20. Sensitivity of combustion costs to this input is medium (SI_N of 0.29).

8.2.10.3 Capital cost of combustion plant

The capital cost used for the base case was 7.3 million USD. Total cost per pit increases linearly with increasing capital cost of the plant (see Chart 8.21). Overall costs have a medium sensitivity to this variable (SI_N of 0.42).

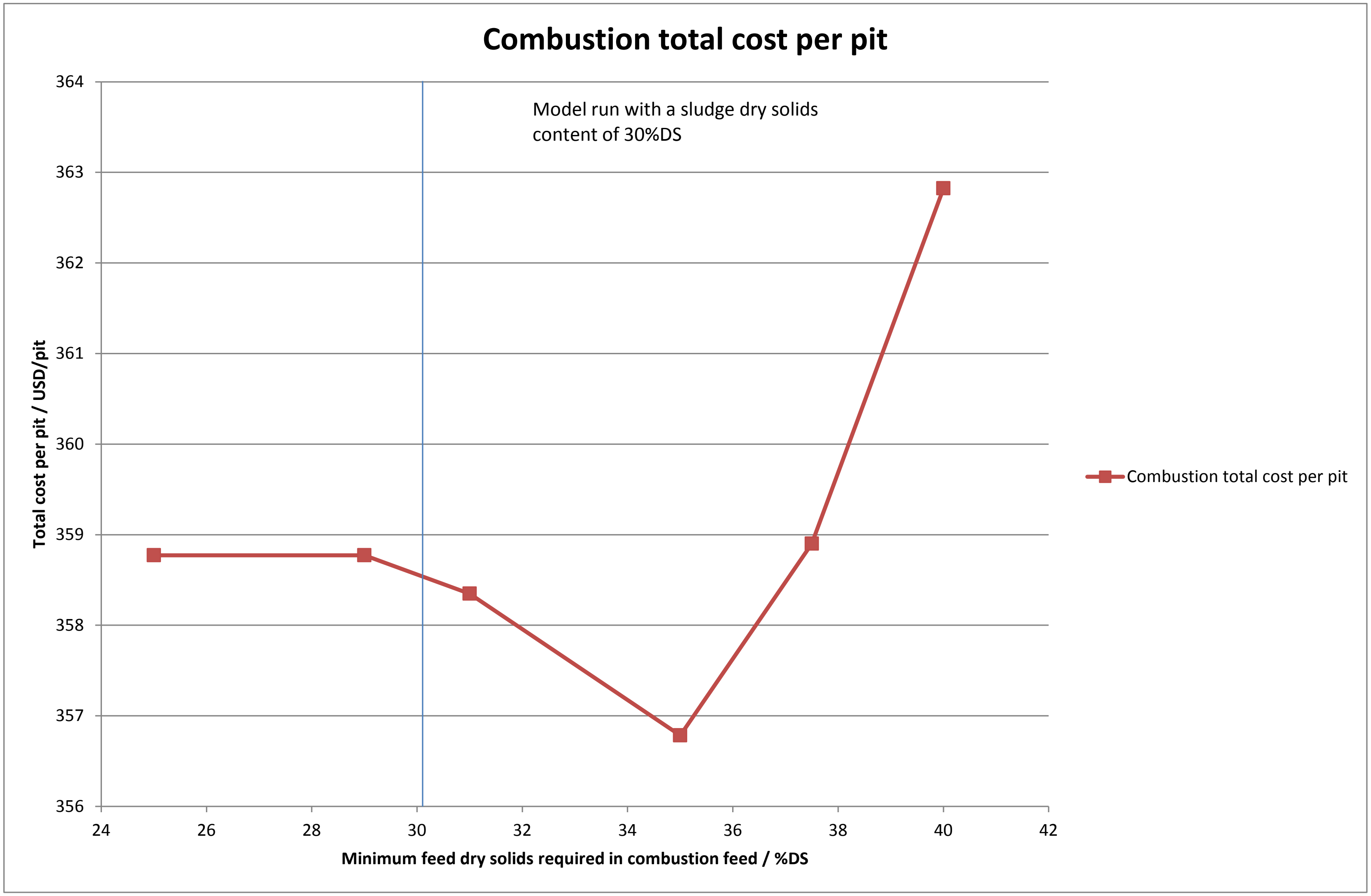

Chart 8.19: Variation of the cost per pit for combustion with the minimum feed dry solids accepted by combustion

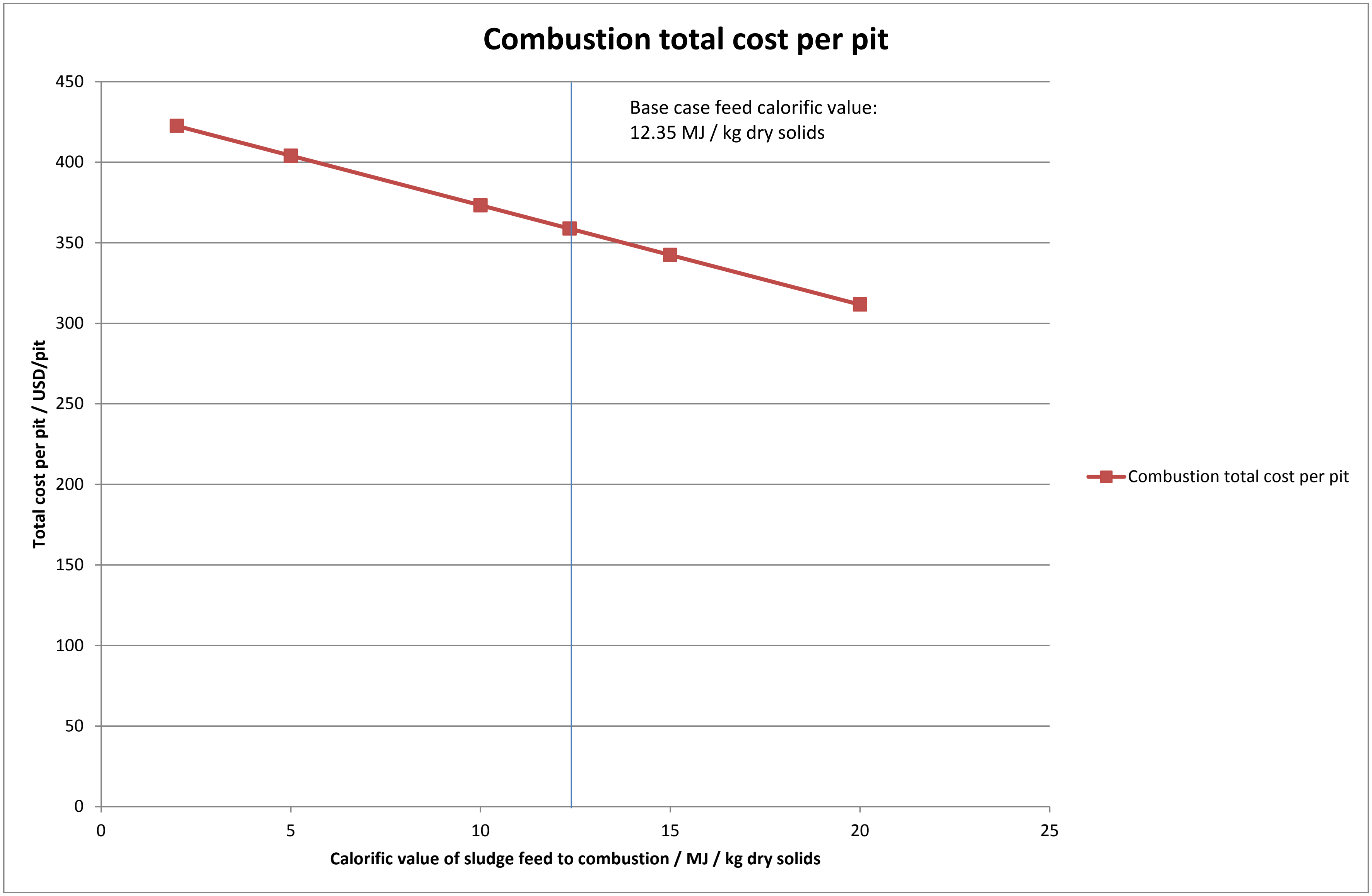

Chart 8.20: Variation in the cost per pit for combustion with the calorific value of the sludge feed

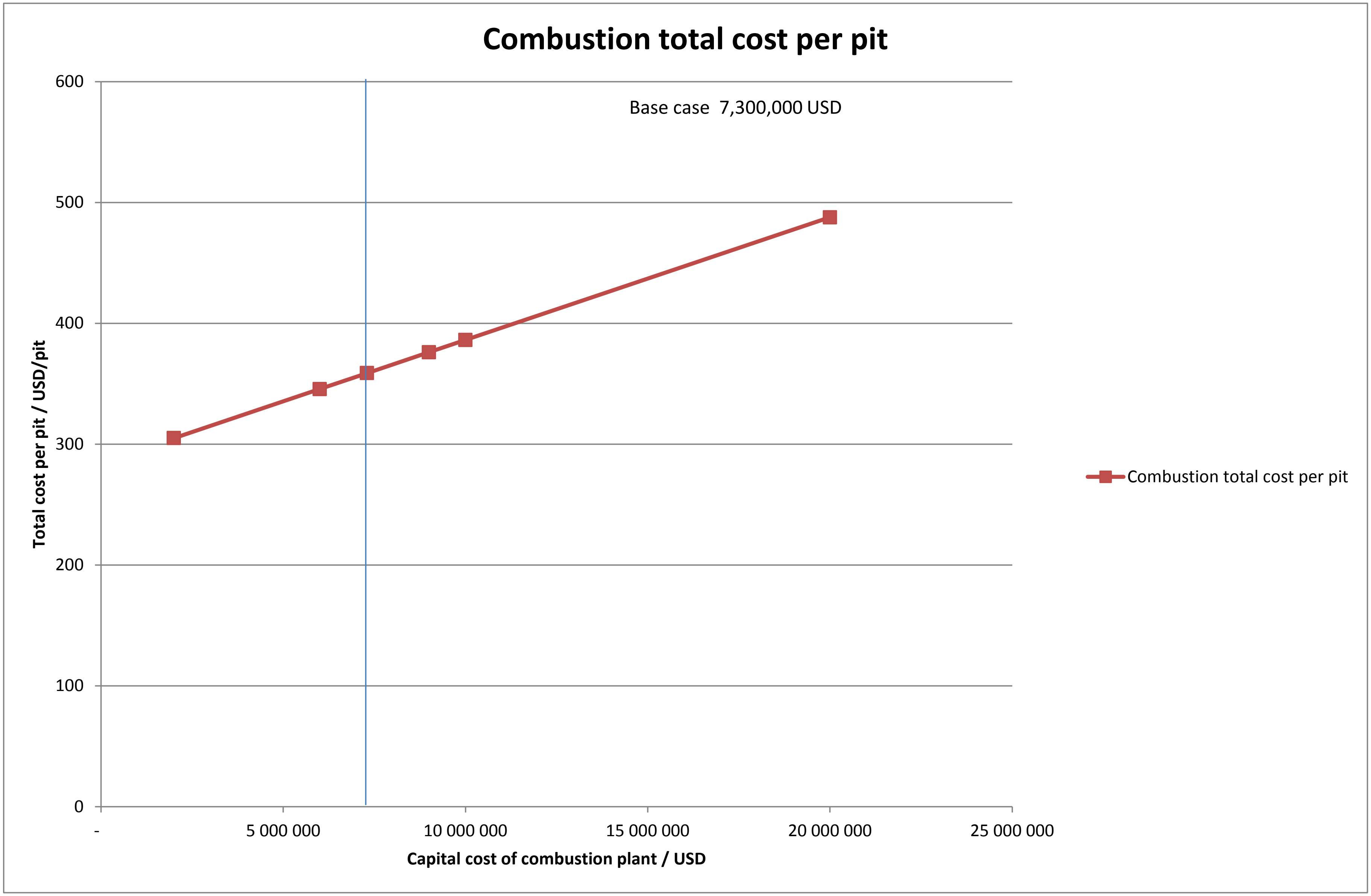

Chart 8.21: Variation in the cost per pit for combustion with the capital cost of the combustion plant

8.2.11 Financial rates

The sensitivity to financial rates cannot be compared between the combustion option and the other two routes, as the cash flow period used for combustion was longer than for the LaDePa process and landfill. The sensitivity of a specific method to a financial rate compared to its sensitivity to other inputs can however be compared, as well as the sensitivity of the LaDePa method compared to landfill.

8.2.11.1 Escalation rate on costs and revenues, excluding fuel

An escalation rate on costs and revenues (excluding fuel) of 6% was used for the base case. Increasing escalation rate has approximately the same impact on the LaDePa process and landfill (SI_N of 0.37 for LaDePa, 0.39 for landfill). Results are shown in Chart 8.22. The cost of combustion was sensitive to the escalation rate, with an SI_N of 0.65.

8.2.11.2 Escalation rate on fuel

An escalation rate of 12% on fuel costs was used for the base case. The impact on LaDePa and landfill costs is small, with SI_N values of 0.05 and 0.01 respectively. The SI_N value for combustion was 0.13. Although, SI_N values for LaDePa and combustion cannot be compared, fuel costs make up a slightly higher proportion of the combustion net costs than for LaDePa, so a higher sensitivity of combustion to escalation on fuel prices would be logical. The tiny increase in landfill costs is due to escalation in fuel costs for conveyance, which contributes to all three methods. Results are shown on Chart 8.23.

8.2.11.3 Discount rate

A discount rate of 9% was used for the base case. Increasing the discount rate causes a linear decrease in the costs for all three methods – see Chart 8.24. The SI_N value was 0.48 for both LaDePa and landfill. The SI_N value for combustion was 0.80.

8.2.11.4 Interest rate on debt

An interest rate of 9% was used for the base case. Changing the interest rate had a negligible impact on the costs per pit for all three methods.

8.2.12 Cost of hazardous landfill

As expected, changing the cost of hazardous landfill has a high impact on the costs per pit of disposing sludge to landfill (SI_N of 0.67). Changing the cost of hazardous landfill does not impact on costs of combustion as it is assumed that all waste can be fed to the incinerator. Costs per pit for LaDePa increase linearly with increasing landfill costs, due to increased costs of detritus disposal, with an SI_N of 0.17. Increasing landfill costs to over 230 USD/tonne (from its current 170 USD/tonne) would make disposal to landfill more expensive than both combustion and LaDePa. At a landfill cost of 100 USD/tonne, LaDePa becomes cost-equivalent with combustion. Therefore finding a different disposal route for the detritus that cannot pass through the LaDePa, or reducing the detritus that occurs in the pits to start with, would be another way to make the LaDePa process more cost-competitive. Results are shown on Chart 8.25.

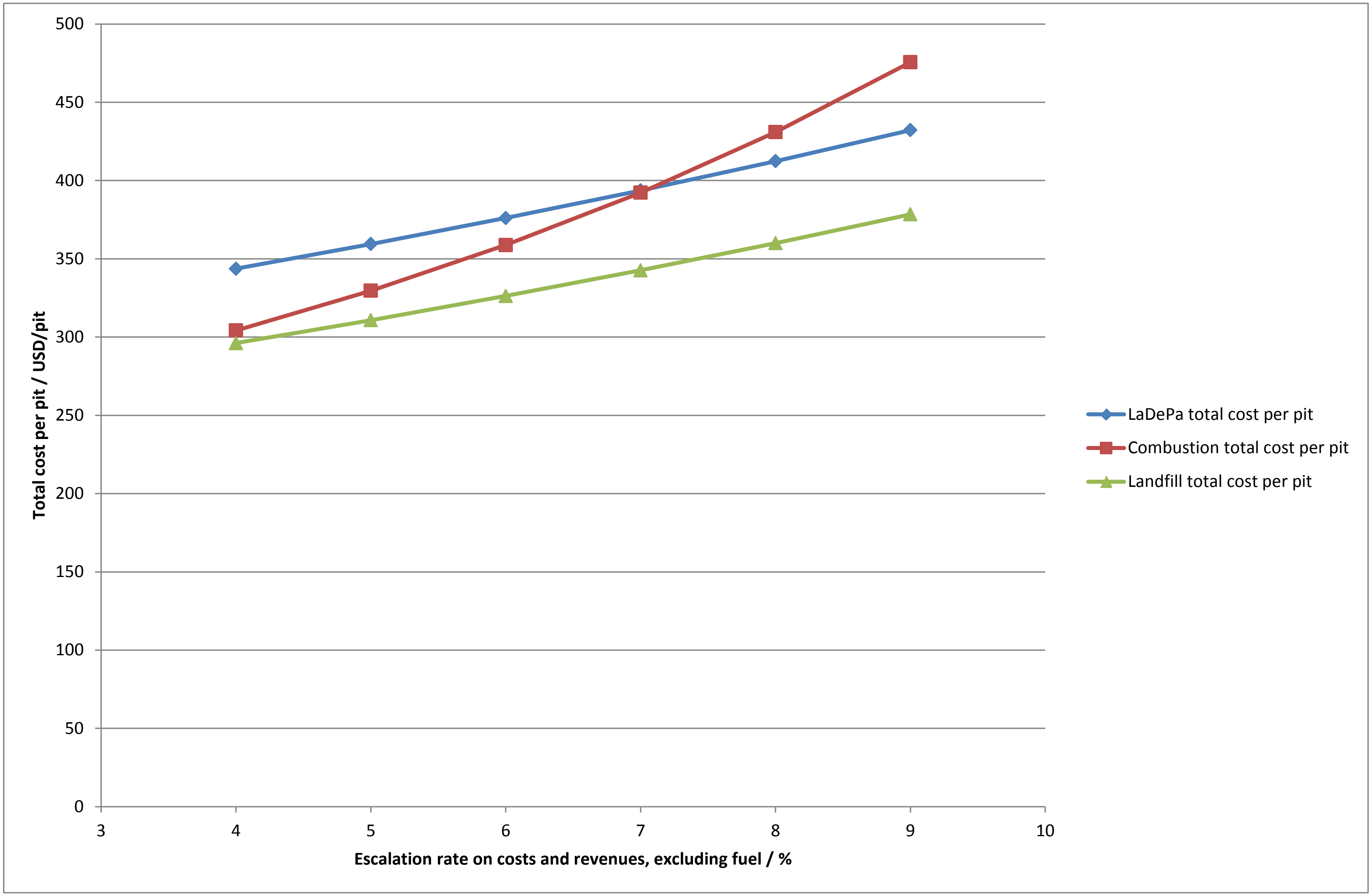

Chart 8.22: Variation in the cost per pit with escalation rate

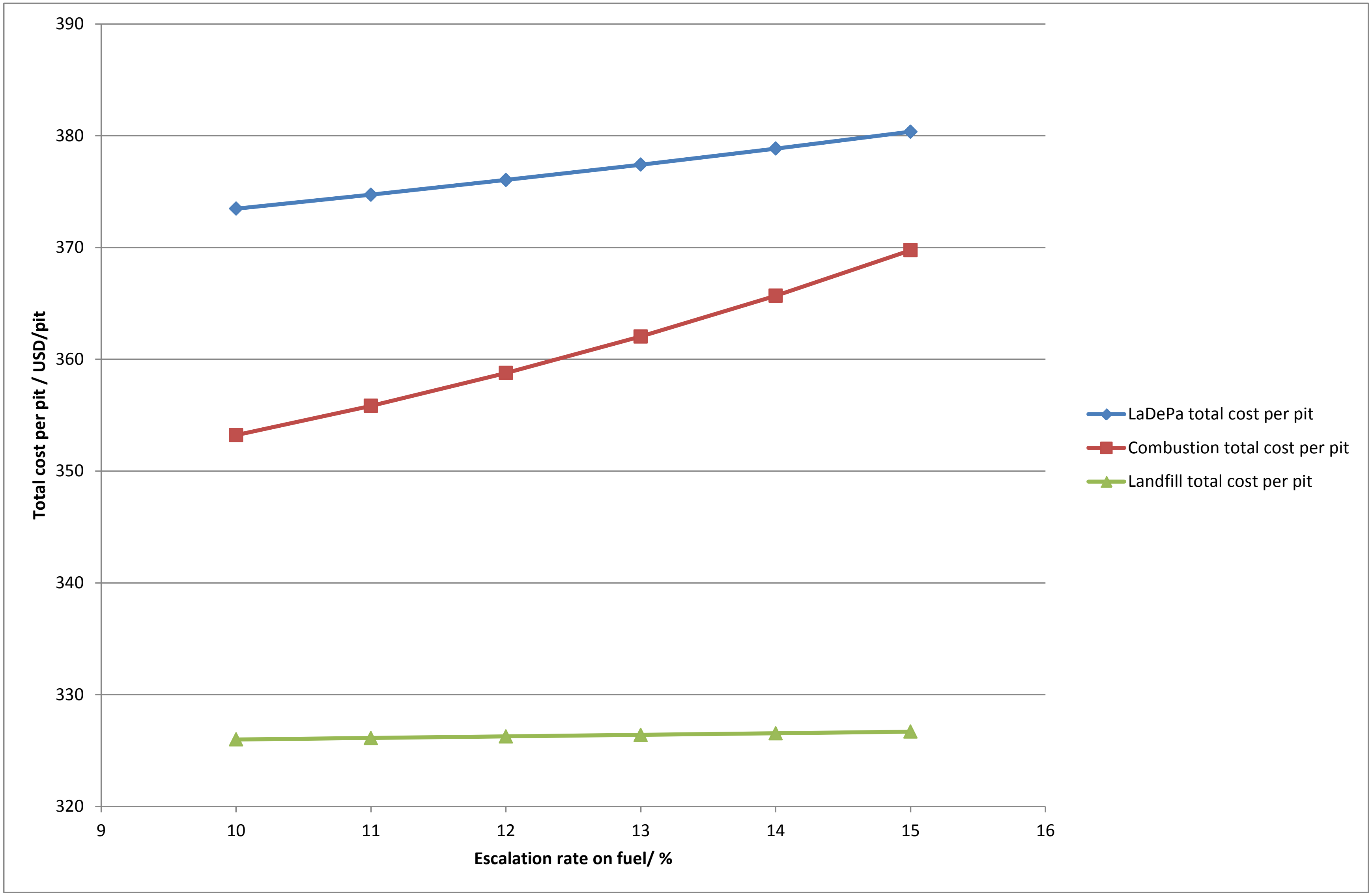

Chart 8.23: Variation in the cost per pit with escalation rate on fuel

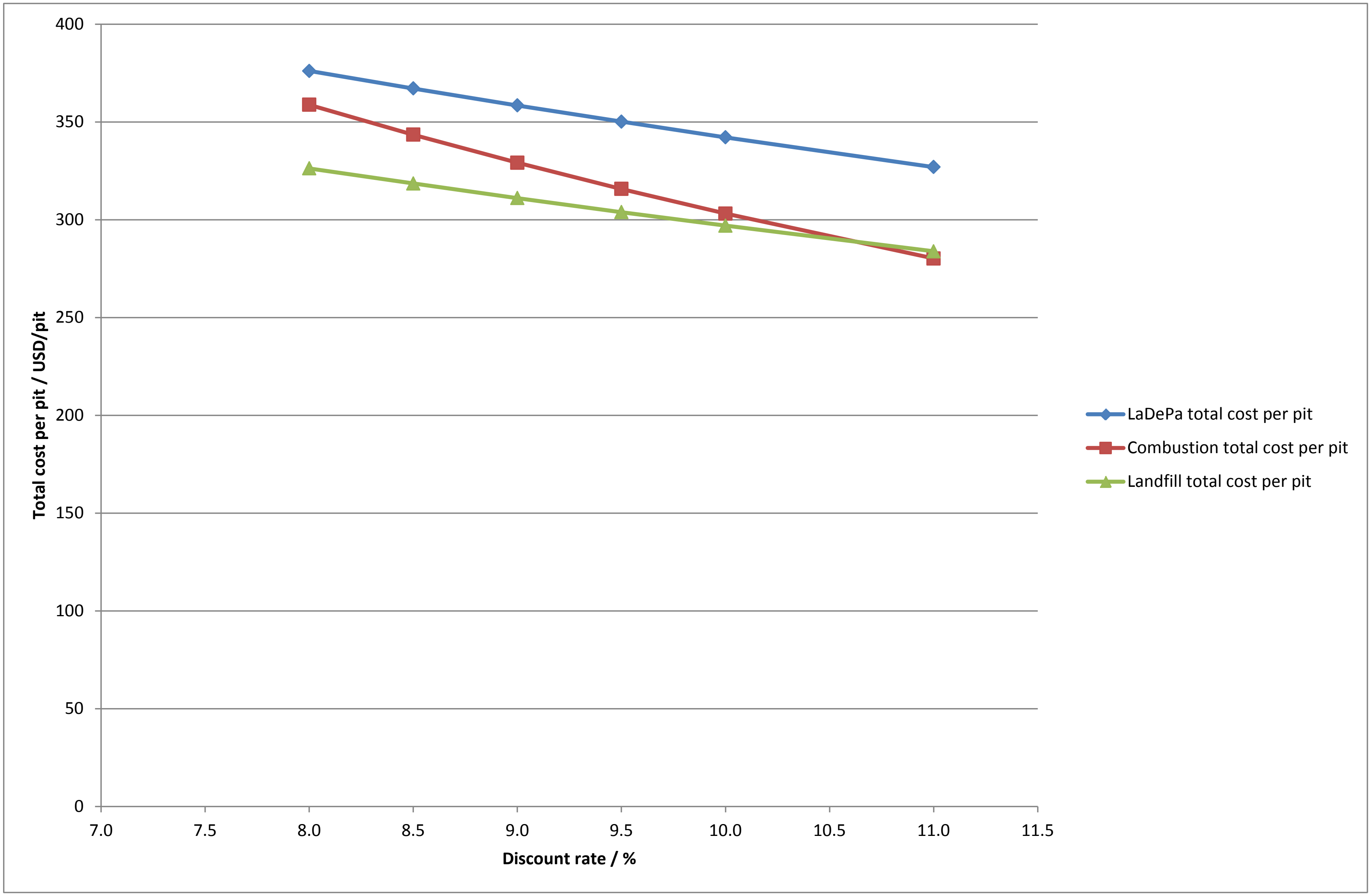

Chart 8.24: Variation in the cost per pit with discount rate

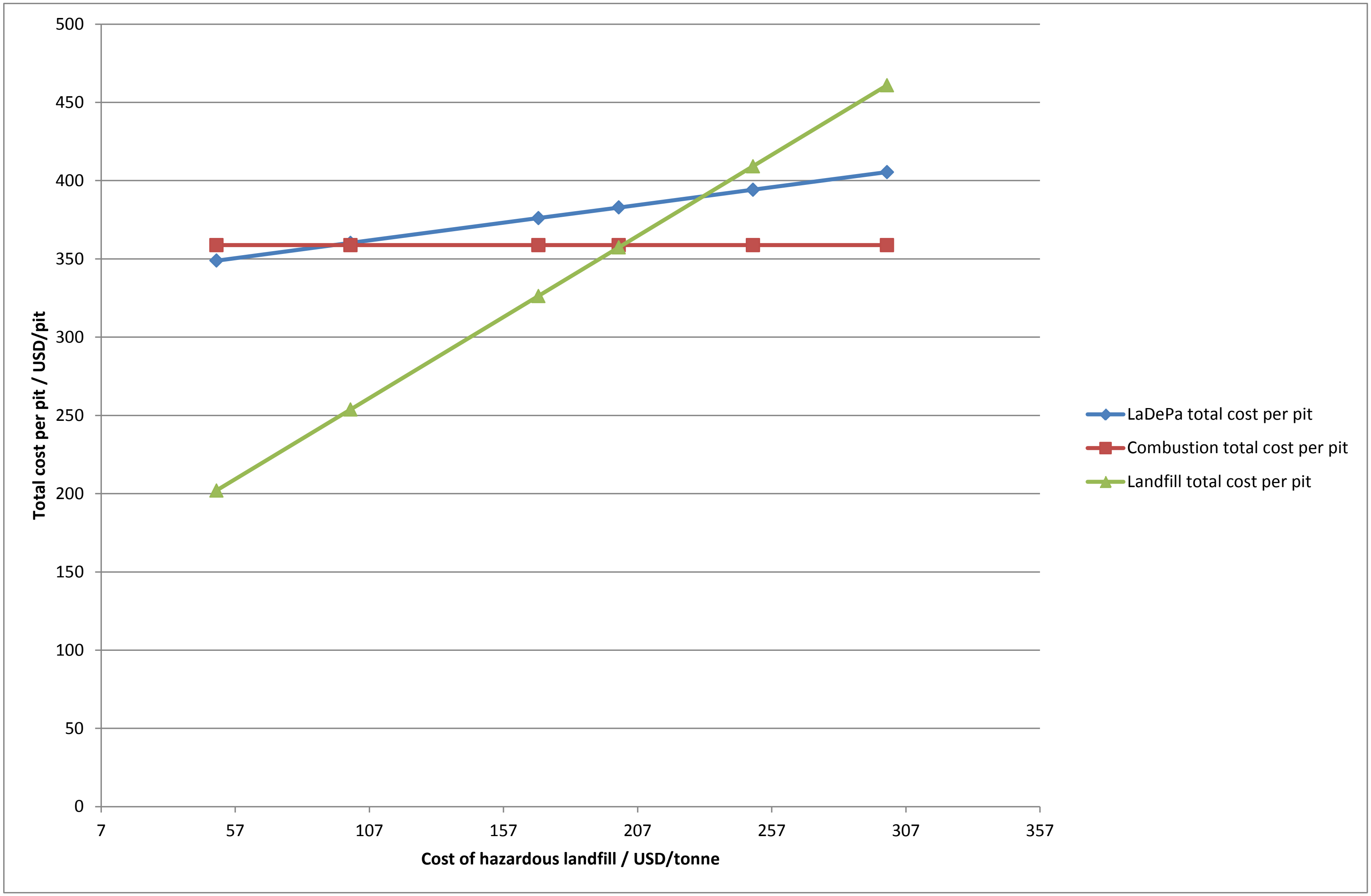

Chart 8.25: Variation in the cost per pit for landfill with cost of hazardous landfill disposal

8.3 Comparison of calculated eThekwini costs to Dakar costs

Table 8.2 compares the costs calculated by the model for FSM in eThekwini to the costs for Dakar. The main differences in the inputs were in the sludge conditions (sludge is at an average of 0.62 %DS in Dakar cf. 30% in eThekwini), the emptying and conveyance methods used (vacuum tanker in Dakar, manual emptying and pick-up trucks in eThekwini) and the costs of pre-treatment (higher per unit volume of sludge in Dakar). Costs for the LaDePa and combustion processes in Dakar were scaled from the eThekwini costs, as local data was not available. Therefore the comparison shows the differences in costs mainly resulting from a difference in the water content of the sludge in the pits.

Table 8.2: FSM cost comparison between eThekwini and Dakar

Cost calculated by model	Units	eThekwini cost	Dakar cost
Emptying & conveyance costs			
Cost per pit	USD / pit	158	45
Cost per tonne of dry solids removed from pits	USD / tonne dry solids	483	422
Overall cost of FSM (emptying, conveyance, treatment and disposal)			
LaDePa			
Cost per pit	USD / pit	376	148
Cost per tonne of dry solids removed from pits	USD / tonne dry solids	1 147	1,377
Cost per tonne of LaDePa pellets	USD / tonne pellets	1 226	1,214
Combustion			
Cost per pit	USD / pit	359	226
Cost per tonne of dry solids removed from pits	USD / tonne dry solids	1 095	2,105
Cost per tonne of LaDePa pellets	USD / dry tonne ash	2 101	4,717
Landfill			
Cost per pit	USD / pit	326	N/A
Cost per tonne of dry solids removed from pits	USD / tonne dry solids	995	N/A

Cost per pit of emptying and conveyance is lower for the Dakar context. This is related to the higher rates of emptying and the lower labour costs due to the use of a vacuum tanker. Costs for emptying and conveyance per tonne of dry solids are similar, due to the high water content of the Dakar sludge.

Overall costs of FSM per pit for LaDePa and combustion are calculated by the model as significantly lower for Dakar compared to eThekwini. This can be attributed to the lower tonnes of dry solids and volume of sludge **per pit** that has to be processed through the LaDePa and combustion plants after pre-drying has taken place. The calculated costs per tonne of dry solids removed from pits are higher for Dakar than eThekwini, primarily due to the higher costs of pre-treatment. These costs are therefore highly dependent on the costs of pre-drying.

8.4 Replication of the LaDePa process on a wider scale

The original aim of developing the economic model was to provide an initial assessment of the economics of using the LaDePa process in eThekwini in order to process pit latrine sludge and the factors that would be significant to consider if the LaDePa process were to be replicated on a wider scale. This section aims to summarise the key aspects that may impact on the scale-up of the LaDePa process, both in eThekwini and in regions outside of South Africa.

Taken alone, and based on the current data available on the LaDePa pellets, the LaDePa process cannot hope to recoup all its costs from sale of the endproduct. However, when LaDePa is compared against the ‘do-nothing’ landfill option, optimisation of operating conditions probably can be undertaken to reduce LaDePa costs below those of landfill and combustion.

Operating conditions fall under one of two types:

(i) Factors that can be controlled by the sanitation service provider to some extent, and therefore optimised to make LaDePa as cheap as possible;
(ii) Factors that cannot be controlled, but where their value has a strong influence on costs. Accurate value needs to be determined to be able to run the model usefully.

Optimising the following operating conditions should be prioritised:

- The number of households included within one pit-emptying programme: the maximum number possible should be included to take advantage of economies of scale and ensure all resources are used at full capacity as far as possible.
- Pit-emptying programme structure: Pit-emptying cycles should follow on directly from one another. Longer cycle lengths are preferable, with cycle length having a greater impact on costs than frequency of emptying.
- Sludge accumulation rates: rates can be reduced by reducing the quantity of detritus disposed of into pits (e.g. by improving solid-waste collection programmes), and designing any new pits to drain effectively. Good solids waste management has a significant impact on the economic viability of LaDePa compared to combustion (for the eThekwini case, where sludge has under 10 vol% detritus, LaDePa becomes more cost-effective than combustion).
- Sludge dry solids content: ideally pits should produce sludge with the appropriate water content to be treated directly through the LaDePa process without pre-treatment, as the costs of sludge drying are high.
- Decentralisation of LaDePa plants: the optimal balance must be found between minimising the distance from the pit to the LaDePa plant and the number of LaDePa plants in operation.
- Minimisation of the distance that the pit-emptying sub-contractor has to travel: use of local pit-emptying sub-contractors will help to minimise overall costs.

In the case of the following operating conditions, the sanitation service provider has little control over the value at which they are set. These values do however have a strong influence on the model outputs, and therefore inputting the correct value for them in the model is important:

- For the LaDePa process specifically, a change in the minimum acceptable feed dry solids and volumetric capacity values will have more impact on the accuracy of the model outputs than the value of the lease rate.
- The wet sludge density impacts on the economic viability of the LaDePa process compared to combustion.
- Financial rates: the escalation rate on costs and revenues (excluding fuel) and the discount rate are the most significant parameters.
- Landfill costs: cost of hazardous landfill may not have to increase by a large amount before the LaDePa process becomes a more cost-effective option, particularly if the detritus content of the sludge is also reduced.

It is not possible to give each of the inputs an optimal value that can be applied generally to any region, as the model and optimisation must be run on a case by case basis.

9 Optimisation of sludge disposal for eThekwini

A full optimisation of the LaDePa or combustion sludge disposal routes for the eThekwini context would have involved determining the ‘ideal’ set of data inputs that would produce the lowest costs per pit. This has not yet been carried out, as further development of the model is needed, including better definition of some of the input values, and a more developed understanding of the relationships between different input values.

As previously described, the review of the model structure and outputs with staff from eThekwini Water and Sanitation formed an important part of its development. This section summarises specific areas where the economic model could be of use to EWS in optimising FSM activities (and therefore potentially to other decision-makers in the sanitation sector).

An overview of the eThekwini context was given in Section 5.2 of this report. There are several factors that make the economics of sanitation provision in eThekwini significantly different to other locations, particularly outside of South Africa. These include:

- Basic sanitation services are financed entirely by the government, in accordance with the constitutional right of every South African citizen to free basic water and sanitation.
- Government-owned land will be used to site the LaDePa and combustion plants and associated sludge pre-treatment and storage operations. Therefore no lease or purchases costs will apply. The pit-emptying sub-contractor will still incur property costs.
- Within South Africa, LaDePa plants may only be leased from the manufacturer, not purchased. This is a specific agreement that has been made between eThekwini Water and Sanitation and Particle Separation Solutions (PSS).
- No income tax will apply to any revenues earned from the LaDePa or combustion operations.

eThekwini Water and Sanitation (EWS) has a structured pit-emptying programme in place. The intention for future pit-emptying cycles is to increase the LaDePa capacity across the municipality, and locate four LaDePa plants as near as possible to the pit-emptying areas that they serve.

The following are ways that the economic model may be of use to EWS:

- Determining the optimal values for parameters that fall under the control of EWS, for example the length of pit-emptying cycle and the proportion of pits to empty, in order to minimise costs;
- Predicting the costs of FSM under different conditions;
- Determining the best methods for pit-emptying, sludge conveyance and sludge disposal under different sets of conditions;
- Understanding the relationships between different operational parameters and their impact on cost, for example the relationship between sludge accumulation rate and sludge dry solids content.

Table 9.1 and Table 9.2 list selected parameters of interest to EWS in optimising FSM activities. Table 9.1 lists those parameters that EWS has at least some influence over. The interest here is in using the model to find the optimal values for these parameters that together produce the lowest overall costs for FSM. Table 9.2 lists parameters that are primarily defined by environmental factors, over which EWS has little control. The object here is to understand more clearly the relationships between these parameters and other parameters, to therefore be able to enter accurate values for these inputs into the model. Table 9.3 provides further detail on the relationships between different parameters.

Table 9.1 Selected FSM parameters under the control of the sanitation service provider and relationships with other parameters

Parameters which can be controlled by EWS Aim for the model: Determine the optimal value for each parameter			
Parameters	**Impact on economics of FSM**	**Is impacted on by these parameters**	**Impacts on these parameters**
Optimal number of members in each pit-emptying team	The rate at which sludge can physically be removed from a pit is limited by the number of people that can access the pit at the same time with tools. However, a significant length of time may be saved in the pit-emptying process by having additional team members who go ahead of the emptiers and open up access to pits. This is particularly important where the terrain makes pits difficult to access. This arrangement is currently in place in eThekwini. Additional staff costs may be offset by the increased speed of pit-emptying. The optimal number of team members could be investigated using the model, also potentially linking this to the terrain conditions of an area.	Rate of sludge removal from pit Number of pits required to be emptied per day per team Terrain and ease of access to pits	
Managing contractor rates	Managing contractor fees are split between: (i) Start of pit-emptying cycle establishment costs (ii) Monthly fees (iii) Fixed percentage of costs The model was used to show the impact on the overall costs per pit of varying the split between these three items.	Length of pit-emptying cycle	
Amount paid for sludge received at the LaDePa sites	EWS intends to incentivise correct disposal of sludge, and more efficient pit-emptying, by paying per quantity of sludge received at the LaDePa site. Although the price paid will be the result of negotiation between the managing contractor and pit-emptying sub-contractor, the model allows EWS to calculate a guide price for the costs of emptying and conveyance under different environmental conditions. The price paid per quantity of sludge may have to be set differently for different areas.	All factors impacting on costs of conveyance and emptying	Quantity of sludge arriving at the LaDePa site

Parameters	Impact on economics of FSM	Is impacted on by these parameters	Impacts on these parameters
Choice to lease or purchase LaDePa plants	Within South Africa, the current agreement between EWS and PSS means that LaDePa plants can only be leased, not purchased, within the country. The model can be used to investigate which scenario is more economically advantageous to EWS, and at what lease or purchase rates.	Financial rates: interest rate, debt: equity ratio, repayment period.	Capital investment required
Number of pits emptied per day per team	During the previous pit-emptying cycle, each pit-emptying team was expected to empty two pits per day. The model allows EWS to estimate the average number of pits possible to empty per day if operating conditions are changed – for example, if much shorter pit-emptying cycles are used and smaller volumes of sludge collected, or if the LaDePa plant is located much closer to the pit-emptying area.	Length of pit-emptying cycle	Optimal number of team members per pit-emptying team
		Frequency of pit-emptying	
		Rate of sludge removal from pit	
		Distances between pit, sub-contractor's base and LaDePa plant	
		Ease of access to pit / terrain	
Frequency of pit-emptying	Pits emptied during the previous cycle had never been emptied, and therefore contained on average 14 years of sludge. The model can calculate the costs over a given period for emptying pits more or less frequently. The frequency of pit-emptying impacts on a number of variables, and therefore calculating its full impact on costs is complex. The model only accounts for some of these relationships.		Nutrient content of sludge
			Calorific value of sludge
			Rate of sludge removal from pits
			Sludge accumulation rate
			Number of pits emptied per day
Length of the pit-emptying cycle	The optimal length of the pit-emptying cycle, independent of the frequency of pit-emptying, also impacts on overall costs.		Fixed costs for each pit-emptying cycle, e.g. managing contractor establishment costs
			Number of pits emptied per day
Proportion of the pit volume to empty	The majority of VIP latrines across the eThekwini municipality are of a similar design and pit size. Shallower pits are faster and safer to empty, or equivalently, only emptying the top portion of a deep pit.	Design of pit	Rates of sludge removal from pits
			Costs of health and safety measures

Table 9.2: Selected FSM parameters defined by context and relationships with other parameters

Parameters over which EWS has little or no control Aim: Determine the correct input value to use for the model			
Parameter	**Impact on economics of FSM**	**Is impacted on by these parameters**	**Impacts on these parameters**
Sludge accumulation rate	Defines the volume of sludge to be handled. Costs highly sensitive to sludge accumulation rate.	Frequency of emptying	Sludge dry solids content
		Sludge detritus content	Multiple parameters in model.
Sludge dry solids content	Defines the mass of sludge to be handled.	Sludge accumulation rate	Multiple parameters in model.
Frequency of emptying	Costs highly sensitive to frequency of emptying.		Nutrient value of sludge
			Calorific value of sludge
			Rate of emptying
			Sludge accumulation rate
			Number of pits emptied per day

Table 9.3 Explanation of the impact of selected parameters on other parameters

Impact of this parameter…	…on this parameter	
Length of pit-emptying cycle	Managing contractor charges	Establishment fees apply at the start of each pit-emptying cycle. This is one of the most significant fixed costs associated with each cycle.
Sludge accumulation rate	Sludge dry solids content	See Section 8.2.3. Sludge dry solids content may alter in direct proportion to sludge accumulation rate (if no solids are lost from the pit), alter independently, or remain constant. Dependent on environmental conditions.
Sludge detritus content	Sludge accumulation rate	Higher detritus content will probably be associated with higher sludge accumulation rates due to (i) higher volumes of material entering the pit and (ii) detritus creating more air spaces in the pit, and a higher level of aerobic degradation which produces a proportionally higher quantity of biomass than anaerobic degradation.
Frequency of emptying	Average nutrient content of sludge	Nitrogen content is likely to be sensitive to the age of the sludge. Unstable organic nitrogen, in the form of urea or uric acid will mineralise relatively quickly within the pit to ammonium, which then converts to ammonia and is lost through volatilisation. The more stable organic nitrogen mineralises slowly to nitrate and ammonium (plant-available forms). This occurs over several years. Therefore the greater the average age of the sludge, the lower the nitrogen content is likely to be. Phosphorus and potassium will only be lost from the pit through leaching. The relationship of their concentrations in the sludge to sludge age will be dependent on the soil conditions and geology of the area.
Frequency of emptying	Average calorific value of sludge	Calorific value is likely to decrease with age of sludge, as the organic content is broken down within the pit.
Frequency of emptying	Sludge accumulation rate	Less frequent emptying may result in lower overall sludge accumulation rates, as a greater amount of biological degradation can take place in the pit.
Frequency of emptying	Rate of sludge removal from pits	It is quicker and safer to remove sludge from a shallower pit, or equivalently to only remove the top layer of sludge from a deeper pit. Both of these scenarios would require more frequent pit-emptying, removing a smaller amount of sludge on each trip. The health and safety benefits and increased speed of emptying might go some way to offset the higher costs incurred by more frequent pit-emptying.
Frequency of emptying	Number of pits emptied per day	Lower frequency of emptying implies a higher volume of sludge to be removed per pit.

10 Future work

The work carried out as part of this project has come only part of the way to assessing under what conditions the LaDePa process could be a wide-scale solution for sludge treatment and re-use.

This work could be further developed in order to make the model more useful to decision-makers in eThekwini municipality and in other locations. The aim would be to develop a more accurate assessment of the conditions under which the LaDePa plant (in particular) would become a competitive sludge disposal route, and what would enable this process to be replicated on a wider scale.

Suggestions for future work can be broadly divided into (i) the refinement of the model calculations and structure, (ii) the obtaining and / or confirming of important data inputs and (iii) linking the economic model with other existing or in-development models.

10.1 Refinement of the economic model calculations

Reference has been made throughout the report to areas of the model that could be further developed. A summary of these areas is given in this section.

10.1.1 Predicting pellet composition and value from feed sludge data

Further sampling of fresh sludge fed to the LaDePa plant and the resultant pellets is needed in order to provide the data for this refinement to the model. It is envisaged that the model would have an in-built capability to predict the changes in sludge composition that take place across the LaDePa process, particularly for those parameters which define the pellets' value as an endproduct – nutrient content, carbon content and calorific value

10.1.2 Enhance valuation of the sludge products: more than NPK content

The greater value of the LaDePa pellets may lie in their nutrient content other than NPK, e.g. calcium, zinc and copper. The pellets are also likely to contain significant levels of organic carbon. Valuation needs to be made on the basis of these components as well as NPK, exploring the possibility of adding LaDePa pellets or combustion ash to conventional NPK fertilisers to provide missing micro-nutrients.

10.1.3 Develop combustion modules

The combustion modules currently rely heavily on literature data. Operational and financial data from a real plant of the appropriate size and configuration is needed to improve the accuracy of results. Energy recovery (e.g. using combustion gases for pre-drying) should also be incorporated. The changes in sludge properties across the process need to be defined.

10.1.4 Valuation of combustion ash as a construction material

The characteristics of ash that make it a good construction material need to be researched. The incineration process conditions that produce a valuable composition of ash must be considered. Assessment of possible markets for ash as a construction material should be investigated.

10.1.5 Determining the optimal conditions for running LaDePa and combustion

Further research work needs to be carried out in order to determine the optimal set of conditions for implementing and operating the LaDePa pelletiser and/or combustion process for the processing of pit latrine sludge in eThekwini. This will be complemented by data from future pit-emptying cycles.

10.1.6 Improving the usability of the model

Several aspects of the model could be developed to make it more user-friendly and accessible to a wider range of users. These include:

- Incorporating a units conversion sheet for input values;
- Automatic generation of graphs showing the relationship between input and output values;
- Improved navigation through the inputs sheet and guidance on input values;

10.2 Missing data inputs

Table 10.1 provides a list of data inputs where accurate values were missing from the current version of the model, for a number of reasons, and notes where other projects in progress may be able to supply data.

10.3 Linking the economic model to related models

Several previous economic models were reviewed to inform the development of this economic model. However, numerous other sanitation economic models exist or are in development, including:

- Economic modelling of FSM in other South African municipalities (MBA project, University of KwaZulu-Natal);
- The NewSan model (University College London) modelling nutrient fluxes through sanitation systems;
- The Omni-Ingestor model: modelling pit emptying and conveyance;
- The VUNA project urine collection model.
- Financial model for incorporation of Omni-Ingestor and Omni-Processor into FSM systems (Boston Consulting Group).

Any future work on this economic model should therefore investigate ways in which these models could complement one another – at the most basic level this could include sharing sets of input data. Comparing outputs of same-function models using the same set of input data would also be an additional way of validating the models (e.g. the Omni-Ingestor model and the emptying and conveyance section of this model).

Table 10.1 List of data inputs missing from the model

Parameter	Detail	Potential source
Nutrient content of LaDePa pellets	Require sampling of multiple batches of pellets of different ages and sludge sources for NPK, other nutrient and organic carbon content.	South African Water Research Commission - Project K5/2317: Characterisation of On-site Sanitation Material and Products: VIP latrines and pour-flush toilets
Parasite content of LaDePa pellets	Sampling of multiple batches of pellets for parasites tested as part of this work (including Ascaris). Sampling of fresh sludge and pellets produced from it to check how effective the LaDePa is at killing parasites. Further analysis of Ascaris appearing as viable in pellets – incubation tests to check viability.	
Other pathogens in LaDePa pellets	Analyse for other pathogens required by the fertiliser regulations but not tested for as part of this work, including FCs and salmonella.	
Heavy metals content of LaDePa pellets	Sample multiple batches of pellets from different sludge sources	
Full analysis of sludge and pellets resulting from same sludge	Ascertain changes in sludge composition across the LaDePa process, particularly nutrient and carbon content and calorific value. Provide data to be able to refine the model to predict pellet composition (and therefore value) for a given sludge content.	
Ash analysis: particle size, nutrients, heavy metals		
Defining the LaDePa operational conditions	Further testing on the full-scale and lab-scale LaDePa plants to determine what the actual operating conditions and ideal feed conditions are. Model was found to be sensitive to several parameters where accurate values are not known, e.g. volumetric capacity.	South African Water Research Commission - Project K5/2317 Characterisation of On-site Sanitation Material and Products: VIP latrines and pour-flush toilets BMGF Global Development Grant OPP 1069575
Agricultural value of pellets	Agricultural trials with LaDePa pellets	

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