Simulation Modelling of Logistics for Handling Bio-Waste from Waste Water Treatment

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Abstract--**Water utility providers are liable for financial penalties and reputational damage for non-compliance with regulations regarding bio-waste handling and disposal. Social responsibility and compliance with regulations can be costly, and this paper discusses a study on approaches for re-engineering logistics processes for bio-waste handling and disposal. The business process simulation model developed during the research has been applied to evaluate and compare costs associated with at least three real operational scenarios on logistics for handling sludge generated in a case study waste water treatment utility.**

I. INTRODUCTION

Utility providers in the water and sanitation sector are required to achieve a triplet of objectives including: a) compliance with regulatory requirements, b) attendance to social responsibility matters, and c) creation of stakeholder value. To achieve these triple objectives, utilities often acquire and deploy available technologies, and/or develop new methods and techniques to facilitate business operations, especially processes for handling bio-waste or sludge from waste water treatment plants. A typical utility may own or operate a number of waste water collection and treatment sites within a wide geographical area, and this creates the need to optimize the logistics for collecting and treating, storing, transporting, and 'disposing' the resultant sludge in a socially responsible manner that concurrently minimises cost and complies with environmental legislation.

A waste water network mirrors a typical supply chain configuration in that, bio-waste collected from each site may be respectively treated before transportation to a storage facility. Each bio-waste collection/treatment point may be considered a node in a network that represents the geographical footprint of a utility's assets and its business operations. To comply with environmental regulations, each collection node (also referred to as an export site) may have its own type of waste transferred to a treatment or 'import' site. Although each node has a treatment capacity, however, the amounts, location, and types of bio-waste existing or generated within the network at any given point in time may be constrained by the finite storage capacities of the respective sites. For instance, the waste collected and transferred to a site at a given time interval may exceed the site's treatment and storage capacity, and the excess will have to be transported to another site.

The location of the respective export/import sites tend to be determined by the demographics of the population and type of residents within a geographical area. Thus, in addition to the applicable by-laws, the spread of physical assets (equipment, land, and plant) required for effective bio-waste management complicate the logistics processes involved. For a relatively large water utility, there may be several export/import sites spread out over a wide geographical area and different municipal jurisdictions. Some sites will have specific rules on operational hours, constraints in terms of the size/tonnage of vehicle that can ply the access roads to a given site, or even the type of treatment allowable (e.g., incineration, sludge-to-landfill, sludge-to-agricultural land and advanced anaerobic digestion). Furthermore, the respective processes at the various sites will incur correspondingly varying operational and logistics costs per tonne of bio-waste handled.

This paper briefly describes the modelling of logistic processes for handling sludge within the waste water network of a privatised utility operator. Section II includes a very brief and concise review of literature on simulating bio-waste logistics processes, resulting in the formulation of a mathematical model used to examine the case study environment highlighted in section III. The results of applying the model to optimise three scenarios of bio-waste transfer between sites are presented in section IV, and the implications of the study are briefly discussed in section V.

II. MODELLING BIO-WASTE HANDLING PROCESSES

In waste water treatment, the pressure of time-dependent compliance to regulatory legislation means that a utility operator must decide on optimal handling of bio-waste on a daily basis. An operator needs to attain efficient and effective control of activities that make up its internal business processes, taking into consideration the realities imposed by both internal and external constraints. In a manner similar to computer integrated manufacturing (see [1]), the bio-waste handling sites more or less constitutes a value chain network comprising many linked activities. Decisions to transport bio-waste within a network of export and import sites are based on data and information derived from activities that inherently encompass a number of variables and physical parameters.

Figure 1 is a block diagram [2] illustration of high level business functions involved in handling sludge from waste water collection and treatment operations. The activities in waste water collection and treatment may be organised as business processes that link people, their knowhow and work methods, information, communication and transactional systems, and all pertinent assets towards creating and

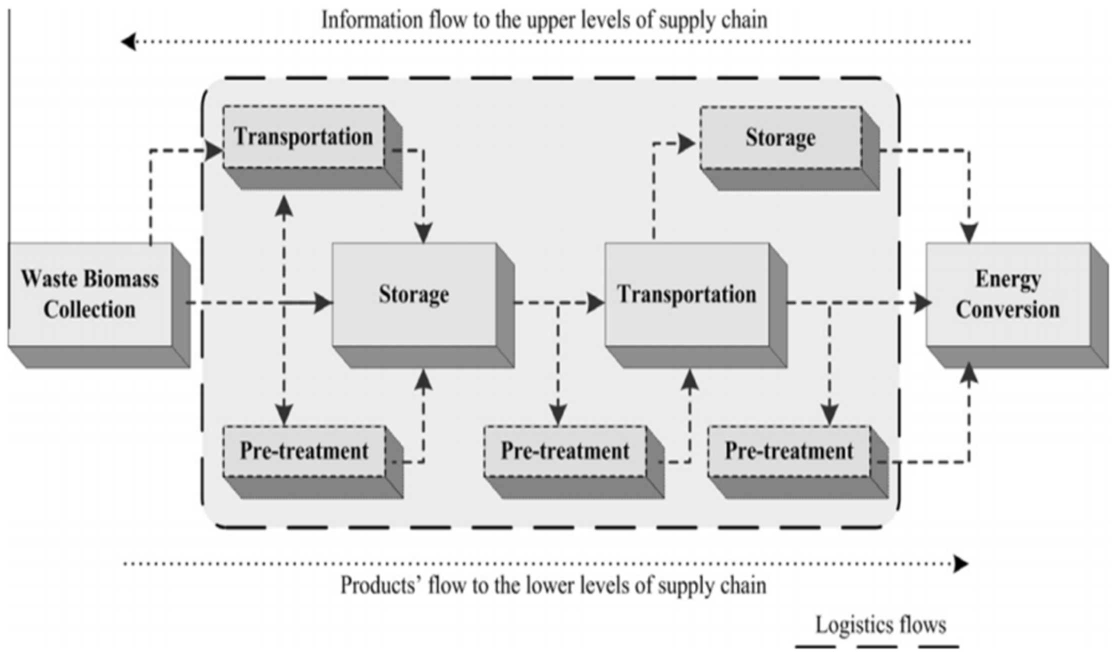


Figure 1: Block diagram representation of waste water collection and treatment

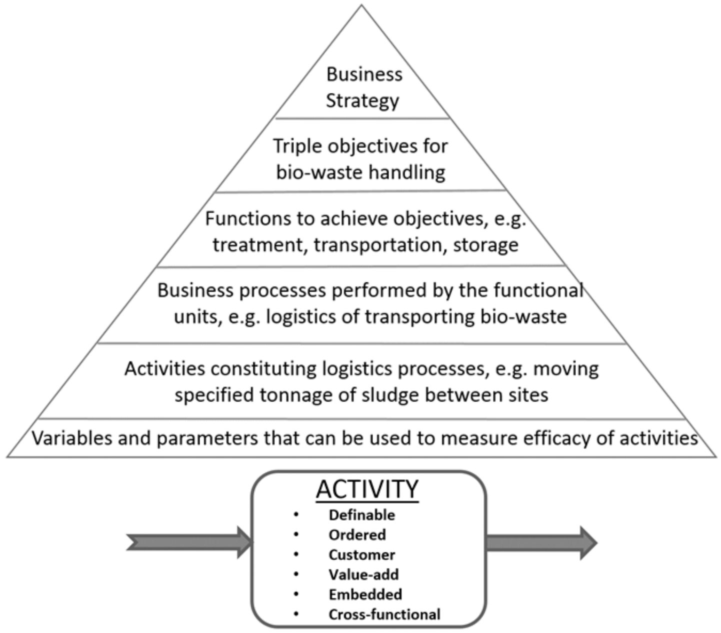
delivering value to stakeholders. For a privatised water utility the stakeholders include the shareholders, the management of the utility, the community, and the relevant regulatory agencies.

The actual operation of the waste water network may generate statistically non-stationary variables and physical parameters, which in turn, can be used to theoretically simulate the business processes implied [3] *apriori*. Using such a simulation model, it is then possible to postulate various scenarios for optimal handling of waste sludge within a network of export/import sites of a water utility. In order for the water utility business to achieve the triple objectives, it is necessary that each activity (plus it associated variables and parameters) has the following attributes or characteristics (cf, [4] and [5]):

i. definability - clear input and output boundaries,
ii. order - positioned in time and space
iii. customer - outcome as input into another activity or decision
iv. value-adding – transform its input efficiently and effectively
v. embeddedness – an activity may not exist on its own without linkages to other activities of an organisation, i.e., towards achieving the triple objectives
vi. cross-functionality – an activity may fan out across other functions

A hierarchical mapping of business functions, processes, activities involved in handling bio-waste is illustrated in Figure 2, and some of the constraints, parameters, and variables that are included in the simulation model are listed.

With regards to the triple objectives, inferences drawn from references [2], [6], [7], [8], and [9] indicate that optimizing the movement of bio-waste between collection points, treatment, and 'disposal' sites offers the best compromise between compliance, social tolerance, and cost. Thus, the simulation model focuses on selecting the optimum route for moving sludge from export to import sites within the waste water network. The logistic variables are distance and time whilst the parameters are location, capacity and quantity of waste at each site. Movement of bio-waste within the network may be constrained by vehicle size/payload, route accessibility, and the stipulation that all sludge at an export site must be moved to import site for treatment and disposal.



Parameters, constraints and variables		
Parameters	**Constraints**	**Variables**
Customer Service	Capacity	Location
Availability	Compliance	Allocation
Response time	Demand	Structuring
Monetary Value		Asset quantities
Utilisation		Echelons
ROI		Sequence
Cost Behaviour		Volume
Information parameters		Outsourcing
Real time communications		Workforce
Connectivity		Inventory level
Risk		
Quality Failure		
Information Failure		

Figure 2. Hierarchical mapping of functions, processes and activities required for bio-waste management.

For the water utility company, a primary goal is to minimize total cost of operations. The main bottleneck with regard to handling bio-wastes is the movement of sludge between export and import sites. Thus, optimizing the logistics processes provides the basis for:

i. compliance with regulatory requirements to move all bio-waste from export to import sites within permitted time intervals and periods,
ii. minimizing the costs associated with collecting sludge from export sites,
iii. minimizing costs associated with bio-waste treatment at import sites.

For brevity, these considerations culminate into the derivation of an objective function to minimize the costs of sludge handling (i.e., both logistics and treatment concurrently). The objective function is depicted in the mathematical equation (1) :

$$\text{Min } \sum_t \sum_e \sum_i \sum_v M_v \frac{\sum_e \sum_i X_{eitv}}{C_v} D_{ei} EI_{ei} + \sum_t \sum_e \sum_i F_i X_{eit} \quad (1)$$

The parameters and variables in the equation are explained as follows.

M_v represents the fuel cost per different vehicle type;

$\frac{\sum_e \sum_i X_{eitv}}{C_v}$ the number of trips per vehicle divided by the vehicle's payload

$\sum_e \sum_i X_{eitv}$ represents the amount of bio-waste collected from export site *e*, and delivered to import site *i*, using vehicle type *v* in time period *t*.

$D_{ei}EI_{ei}$ represents the distance between an export site *e* and import site *i*

$\sum_e \sum_i F_i X_{eit}$ represents the cost of treating all the sludge X_{eit}, delivered at the an import site within time period *t*.

The derivation of the mathematical model in equation (1) takes into consideration:-

i. amount of waste flowing to export sites,
ii. vehicle sizes and access rules between sites,
iii. distances between respective export and import sites,
iv. technology type, and
v. capacity limitations at respective export sites.

The model was applied to examine a number of operational scenarios for handling sludge in the waste water network of a case study utility.

III. CASE STUDY ENVIRONMENT

The privatised water utility company operates a "source-to-sea" scope, and includes assets deployed for:

i. extraction of raw water from inland sources,
ii. treatment and supply of clean water to consumers,
iii. collection and treatment of waste water streams, and the
iv. return of treated water to the sea and/or rivers.

The company is organised into a number of operational 'business units' but, the units most relevant to bio-waste handling are:

- Treatment Operations - preparation and pre-treatment of bio-waste at the export sites. The waste must be prepared according to certain criteria (thickness and age) to ensure that it is suitable for transportation and final treatment at the various import sites. When the waste at a site is ready for collection the site is 'triggered' – meaning that the waste must be collected and transported to meet social and regulatory compliance targets.
- Waste Operations - transportation of waste, final treatment of waste, bio-waste energy generation and final disposal of waste. This business unit is thus responsible for the logistics of collecting and sending waste to the most suitable import site for final treatment and disposal.

A cross functional view of the company's waste handling logistics chain is illustrated in Figure 3.

The geographical area covered by the waste water network is approximately 11900 km^2, contains about 32000 kilometres of waste water piping and includes various commercial, industrial businesses plus nearly 2 million residential properties. Consequently, the composition and quantity of bio-waste stream varies between export sites, and correspondingly, different treatment technologies are respectively utilised at several import sites. Apart from externalities, the transfer of various bio-waste streams between numerous export and import sites, using variously sized vehicles, present a plethora of logistics scenarios for the utility operator.

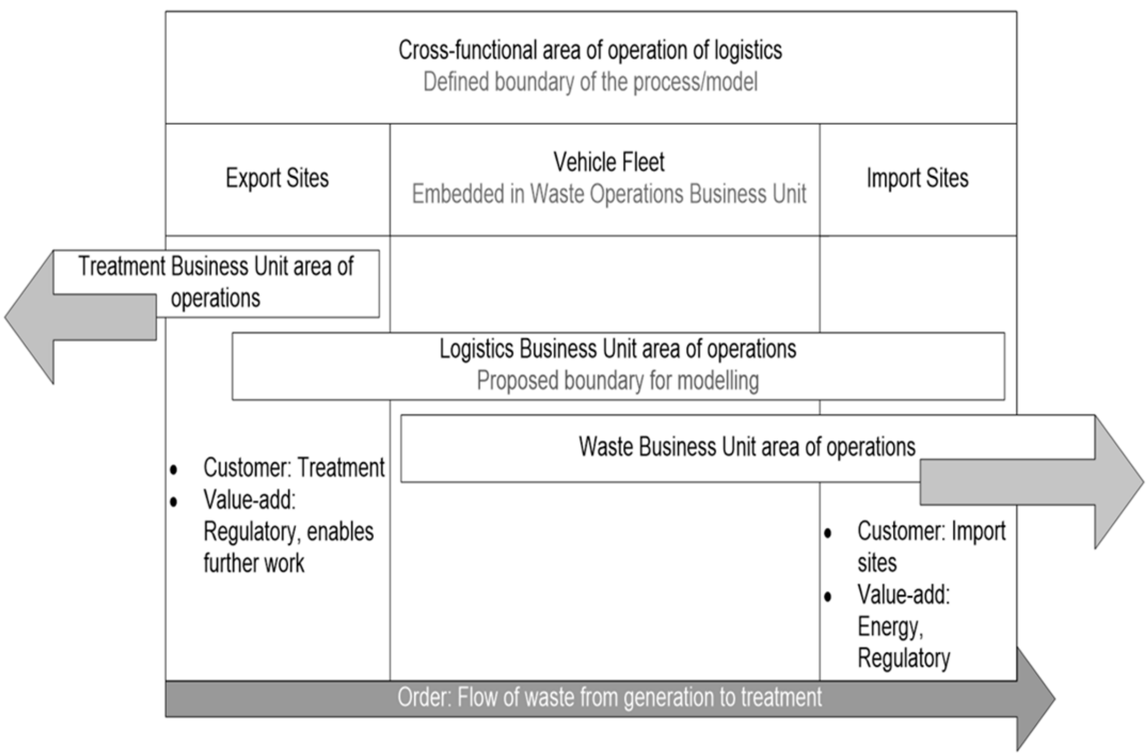


Figure 3. A cross functional view of the case study waste handling logistics chain

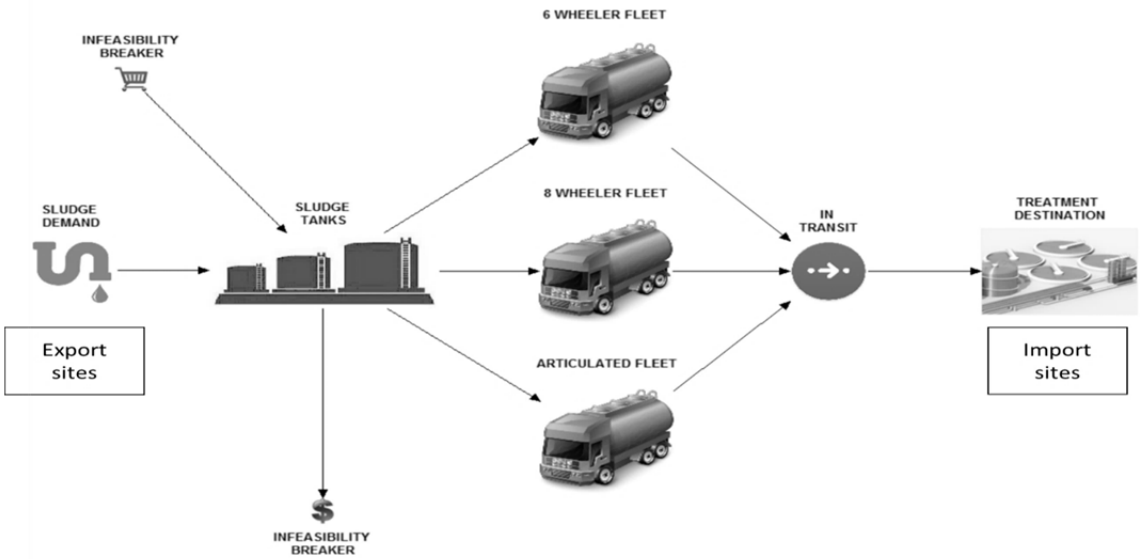


Figure 4. Asset footprint for logistics handling of bio-waste water streams.

The picture in Figure 4 depicts a footprint comprising:

- over 600 export sites
- over 20 import sites, also called treatment works, which can only process a finite amount of waste on a daily basis, each one with its own treatment cost per tonne processed, plus
- a fleet of vehicles in 3 different sizes/capacities (not stated for confidentiality reasons).

The mathematical equation (1) was applied to examine scenarios that will lead to cost-effective handling of the waste sludge between export and import sites. The optimal cost for each scenario is intended to provide guidance on how to organise/re-organise activities performed by the utility so as to optimise the logistics processes for handling bio-waste in a socially responsible manner, whilst concurrently complying with stringent regulations.

IV. CASE STUDY SCENARIOS AND RESULTS

The mathematical equation (1) was converted into a software program, using Enterprise Optimizer® tool. The tool converts the graphical representations of processes together with back end data and applies linear programming, mixed integer programming, and constrained-oriented reasoning to optimise a selected objective function associated with each scenario. Empirical data from 391 export and 18 import sites within the case study environment was used to optimise the cost objective function for the following three scenarios:

- Baseline Scenario – replication of legacy mode of logistics processes to establish a baseline of total costs and distance travelled whilst moving a volume of 435440 tonnes of bio-waste.
- Scenario 1 – determination of optimal import site based on historical values of capacities for 10 geographically closest import sites. Historical values were derived from an analysis of actual performance of the import sites over an applicable time horizon. Volumes treated were tracked over a defined time period to determine what the daily average capacity was.
- Scenario 2 – determination of optimal import site based on plant design specifications for 10 geographically closest import sites. Plant design specifications are the perceived theoretical maximum treatment capacities based on an estimation by subject matter experts in the organisation. This is the capacity that could potentially be achieved in a "blue sky" environment of thorough maintenance, no critical asset failures or any frequent unforeseen disruptions.

The optimised costs for the three scenarios are compared in terms of: a) number of trips done by the vehicles, b) distance travelled by the vehicles, and c) the total costs of transportation and treatment. The results are summarised in the bar graphs in Figure 5.

Figure 5: Summarised costs for the respective simulated scenarios

The fuel costs to meet compliance for each of the different scenarios indicates that the 'baseline' logistics scenario will have the lowest cost in comparison to scenarios 1 and 2, corresponding to the fewest trips and lowest distances travelled by the vehicles. Interestingly, the treatment costs for the baseline case is conversely the highest among the three scenarios. Whereas the fuel costs for scenarios 1 and 2 are respectively 13.15% and 10.53% higher than the baseline, however, the treatment costs are respectively 26% and nearly 50% lower. Furthermore, for scenarios 1 and 2, the average cost per tonne of waste processed are respectively 20% and 40% lower than the baseline case. The optimised costs for the baseline scenario were based on actual historical treatment capacities, whereas the design values were used for scenarios 1 and 2. The point here is that design specifications do not always reflect the operational volatility experienced in the treatment network. Import sites can be extremely susceptible to changes in weather conditions. This affects the rate of bio-digestion and result in operational inefficiencies.

V. SUMMARY

The results from other scenarios provide indications as to how the organisation may re-engineer the logistics processes for handling bio-waste in order to achieve the triple objectives opportunities. At first glance, the baseline scenario may be preferred when performance is measured on fuel costs and distance. Scenarios 1 and 2 suggest that triple objectives can be optimized, and thus signals opportunity to re-engineer the business processes involved in handling bio-waste in waste water networks. Whereas this traditional measurement of logistics performance often excludes vital aspects of bio-waste handling such as socially responsible treatment and disposal, however, the results here indicate that it is possible to reduce costs whilst improving asset utilisation.

Inadvertently, some of the re-engineering may involve re-aligning the activities of the respective business units towards achieving optimized handling of bio-waste streams. This requires that the overall footprint must be considered instead of the conventional approach of demanding and comparing each business unit in terms of lowest cost. In fact, the re-engineering should include re-organising the business units beyond conventional structures, something that a utility company tends to vigorously resist, partly because of convention, the large asset base and wide geographical spread. The results of the study reiterate the importance of using simulation models to aid decision making especially in situations that inherently involve complex choices such waste water sludge handling.

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