

## An Interface-Based Method for Performance Improvement of the Municipal Solid Waste

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### ABSTRACT

*The municipal waste stream is evaluated within an operations context for the purpose of deploying interface management to improve performance. Using a set of nine municipalities in Limpopo Province, South Africa, stratified random sampling produced 225 observations made up of collection, treatment, and landfill sites. Field observation and repeated measurement of eight predictors and one response variable were used to collect data, followed by an experimental set of 29 sites where a three-cycle treatment of loadings was used to record changes in the response variable. A primary data set was initially entered into Excel to generate descriptive statistics. Multiple linear regression and correlation were performed using the stepwise option after testing for normality and collinearity. The results show statistically significant final models ( $F(1,221) = 1093.23, 105.77, p.001$ ), with an adjusted  $R^2$  of .040 and a 95% confidence level. Technical and managerial problems in waste management are critical at interfaces that provide ideal sites for targeted interventions to accelerate the rates of waste flow to landfills. The contribution of the study lies in the development of an interface-based method for improving the performance of the waste stream. The implications speak to issues of waste management that feed into concerns about sustainable urbanisation today.*

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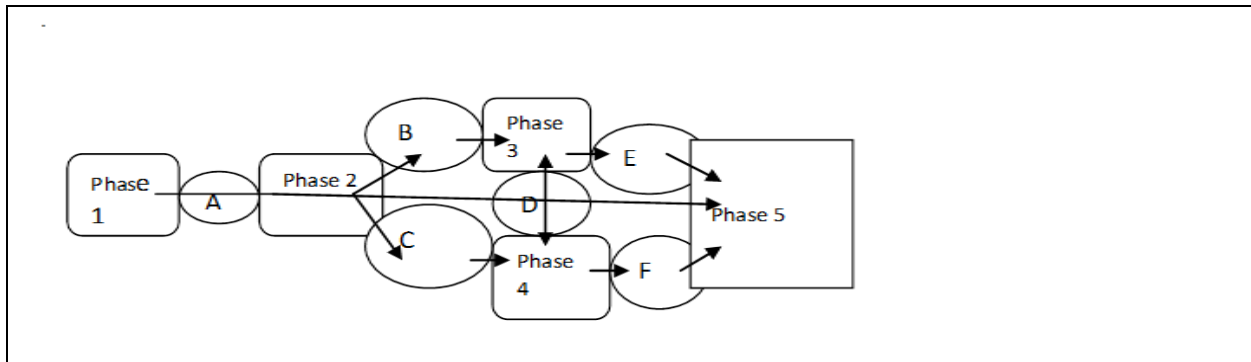
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### 1.0. Introduction

The solid waste stream is an open system (Pires et al., 2011; Seadon, 2010) that represents physical and human interactions. Its physical components are part of a natural system (Marshall & Farahbakhsh, 2013) and can be manipulated to generate system outputs at the end (Eriksson & Baky, 2010). Its human dimension brings people and firms on board. The human component is difficult to treat within a system's environment because the behaviour of players cannot be predicted. The blurred boundary between physical and human system components creates peculiar problems for researchers (Ziegler & Ott, 2011). In general, theoretical developments allow such limitations to be overcome, especially in research projects dealing with problems of performance in waste management. A significant percent of cities in the world show weaknesses in their solid waste management systems (Ferrer & Alba, 2019; Gutberlet et al., 2017). Delivering an efficient solid waste collection, processing, and disposal system creates increasing demands, driven in part by high rates of urbanisation. In practice, it should be possible to intervene to cause a faster flow of waste. An efficient system should not allow waste to pile up along the stream anywhere (Garcia & You, 2017). Such interventions should be sensitive to the ripple effects that go with the waste stream. Without this, any interventions that accelerate the rate of waste flow at

one stage may in fact create severe bottlenecks and system failure (Bugge et al., 2019). There has to be an embedded mechanism for information transmission and management between the various components. It is not surprising, therefore, that contemporary literature puts so much emphasis on the design of integrated waste management systems (Siragusa & Arzyutov, 2020). What is often overlooked is that managing the interfaces between system components is equally important. Every system is made up of inputs, processes, and outputs (Fig. 1), where inputs are in the form of energy, materials, and information. Process covers all activities that convert the inputs into some form of service, finished product, or semi-finished product. Outputs are the end deliverables of the particular system. In the case of the waste stream, this may be recovered products, recyclable products, and non-recyclables. In the present case, the municipality is responsible for the operations of internal and external interfaces as they relate to the waste stream. For the waste stream, the central focus is on how to reduce the time lag in operations between the phases and, in the process, achieve some kind of time compression with multiple benefits in terms of time, cost, savings, and efficiency. In Fig. 1, phases 1, 2, 3, 4, and 5 are separated by interfaces labelled A, B, C, D, E, and F, representing pauses.

Fig. 1  
*The Municipal Solid Waste Stream*



In Fig. 1, phase 1 deals with composting at the source, collection, and temporary storage. Phase 2 deals with central treatment, which includes waste separation and

sorting. Phase 3 includes diversion into stockpiling and recovery. Phase 4 deals with waste treatment, with offshoots into incineration, waste-to-energy, and

recycling. Phase 5 deals with landfilling and potential reverse loops back to the environment. Transport links all these phases to facilitate waste movement, while Route AD is a direct conveyor where all collected waste is forwarded to the landfill. Improving the speed at which the flow rate in the waste stream is accelerated across interfaces means that it is possible to reduce the time spent on carrying out tasks associated with each interface. Time reduction means that more and more waste is moved between generation and treatment (Bugge et al., 2019). In theory, it is possible to achieve time compression at each interface. In theory, then, it is possible to minimise waste volumes delivered to the landfill. But this calls for high levels of waste recovery, diversion, and recycling along the way. This is the ideal, but due to technical, environmental, and managerial constraints, it has yet to be realized. This study attempts to bridge this shortfall in the state of knowledge on the behaviour of the solid waste stream. To this end, three objectives are specified: (i) characterise the waste stream; (ii) analyse waste operations at interfaces; (iii) identify imbedded limitations thereof; and (iv) develop an interface method for improving performance. In systems theory, several positions are advanced to demarcate the present study. The municipal solid waste stream is both a natural and a social system. By necessity, therefore, the applicable theories should ideally capture this overlap between the natural and social environment systems (CHES) (Liu et al., 2007), the common terms for such a combination of systems. Theoretical advances that fall into this class include complex adaptive systems (Preiser et al., 2018); complexity theory (Manson, 2001; Manson & O'Sullivan, 2006); and dynamical systems (Ionides et al., 2006). The research problem centres on how to intervene in the flow of waste between phases of the waste stream, which ultimately ends at final disposal landfill sites. Such an intervention calls for studying the current behaviour to identify deviations from an efficient waste delivery system where such departures undermine the sustainability of the waste delivery system itself. Such an exercise calls for an understanding of the mechanics of waste flow across time and sites in a linear trajectory from collection to disposal. Through experimentation, changing control inputs allows for the

generation of observation data on the basis of which it is possible to model the most efficient input-output quantities for the entire waste stream. Parallel to experimentation is a learning component for both the waste directorate at the town/city level and the waste workers, which feeds into the municipality as an organisational structure for the delivery of specific public services. Using this rationale, theories that talk about systems and sub-system change appear to offer opportunities for tackling the research problem. Efficient waste delivery systems should achieve a drastic reduction of waste along the waste stream and feed into approaches around waste minimization and sustainable urbanisation (Bugge et al., 2019). Conventional waste management frameworks (Siragusa & Arzyutov, 2019) across all South African municipalities are complete packages that are multi-purpose in terms of coverage. Similar conditions apply across Sub-Saharan Africa (Kabera et al., 2019). These frameworks, however, are silent on waste stream operations or waste delivery expectations (Romano et al., 2019). While several elements are common in these frameworks, it is noted that there is no dominant one. There is justification for reconfiguring this organisational structure. It is in this context that ideas from systems theory become applicable.

## **2. Materials and Methods**

### *2.1 Ethics Statement*

This study did not include animal and plant species. No environmental specimens were collected from the study sites. Where human populations were observed in their work environments, care was taken to ensure that their rights to privacy were respected. This study did not include the collection of information from any vulnerable groups through interviews.

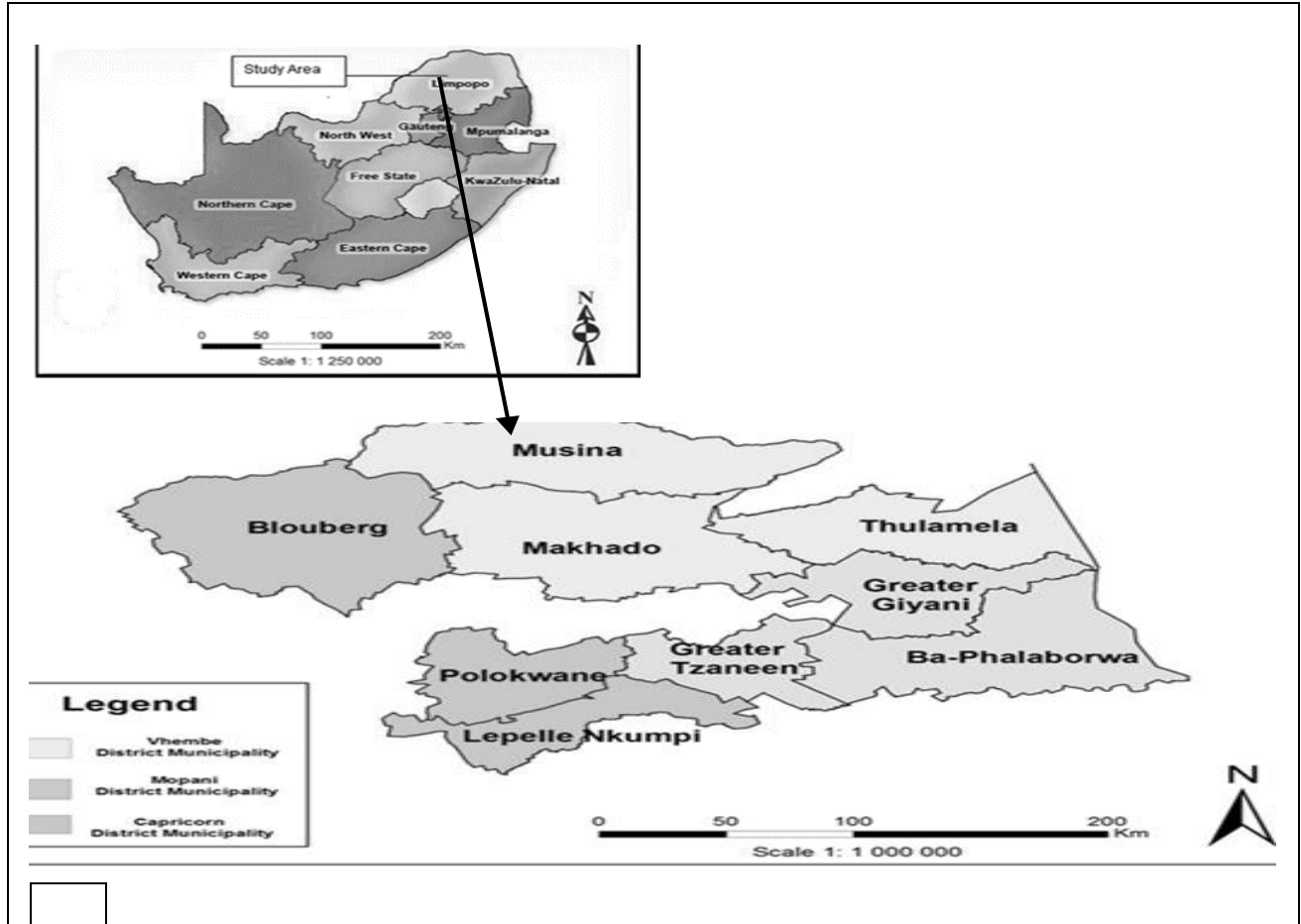
### *2.2 Study Area*

Management of waste in South Africa is delivered by municipalities, with the national government handling legislative, policy, and planning responsibilities. A set of nine municipalities in the Limpopo Province (Fig. 2) were selected based on each having a significant urban area in terms of population as of 2018 estimates (StatSA 2018). At street level, waste collection deals with

commercial, industrial, and residential areas where receptacles of various sizes are positioned to receive waste until collected by municipal workers. The conventional solid waste stream is made up of

Fig.2

Municipalities in Limpopo province of South Africa



### 2.3 Data Sources

Depending on the actual parameters of experimentation, interest in this case centres on a set of observations and measurements to generate primary data inputs into analysis. The most important waste pathways from generation to final disposal, as measured in terms of collection, recovery, transportation, transfer, treatment, and final landfilling, can be identified to form the basis of interventions. The total number of waste sites at the time of the study came to 645. Apportionment for each municipality and the use of stratified random sampling generated a sample size of 225 sites, made up of 169 collection sites,

temporary collection sites with bulk metal skips for temporary storage. From here, waste is loaded for transport by specialised waste trucks and tractor-drawn trailers to treatment centres and landfill sites.

45 landfills, and 11 treatment facilities. Data collection covered eight predictor variables and one response variable. For each site, repeated measurements were carried out once a week for a month, generating a set of four values per site from which a mean value was computed. Field workers received a waste collection schedule from the municipal waste directorate, indicating the days and times when workers would be at each collection site. The same schedule was used to retrieve data on the frequency of collection per week (X1), on X2 (waste workers) deployed per site, and on X7 (supervisors). Field workers were distributed across the entire study area to ensure that each of the 255 sites

was covered. For X5 (specialized trucks), X6 (front-end loaders), and X8 (tractor-drawn trailers), they were counted at the individual sites, and values were entered into a spreadsheet. Field workers carried out observations and measurements during the actual clearing of waste at each site. The results are reported in Table 1. An experimental set of sites was established using a random sample of 29 sites apportioned as follows: 23 for collection, 5 for landfills, and 1 for a treatment facility. A treatment schedule made up of 4 cycles was run for these sites as follows: In cycle 1, mean values from field results earlier collected are carried forward into row 1 of Table 3. In cycle 2, X1 (collection) and X2 (number of waste workers) were all increased by a factor of 1. In cycle 3, a supervisor (X7) was present at each site where waste was being loaded onto a specialised truck (X4). In cycle 4, a front-end loader was used for all sites without a bulk metal skip. A specialised truck was used for sites with a bulk metal skip. The loading time was recorded for each of these cycles. The experimental results with loading time as the dependent variable are reported in Table 3.

#### 2.4 Statistical Analysis

Field data was input into an *Excel* programme for generating descriptive statistics and later imported into the *SPSS* programme for further analysis. Initial tests

were carried out to ensure that assumptions of normality and collinearity were not violated. A multiple correlation and regression analysis was conducted to see if a set of managerial and technical variables predicted the loading time of waste at each interface of the solid waste stream. One research hypothesis ( $H_1$ ) was advanced: mean loading time in minutes per collection site is positively attributed to a specific set of technical and managerial inputs at interfaces. The null hypothesis ( $H_0$ ) asserts that there is no effect of predictor variables on the response variable. The criteria for rejection are that the  $p$ -value in the regression score on the ANOVA output should be less than 0.05. The overall significance of predictor variables in the model is established using Snedecor's F-test.

### 3. Results

#### 3.1 Characterisation of the Municipal Solid Waste Stream

Field data appearing in Table 1 shows that apart from *loading time* (Y),  $N = 225$ ,  $SD = 10.52$ , the rest of the variables show a convergence close to the mean. Across the entire study area, a mismatch is noted between the number of *workers* (X2) employed for waste collection and those found working at various sites. The former was consistently recorded at a higher value than the latter.

Table 1  
*Descriptive Statistics of Measurement Variables*

	N	Minimum	Maximum	Mean	Std. deviation
X1 Collection	225	1	5	2.30	.943
X2 Workers	225	3	9	5.46	1.030
X3 Volume	224	.3000	4.0000	2.025446	.9339269
X4 Trucks	225	0	3	1.17	.860
X5 Skips	225	0	2	.45	.525
X6 Loaders	225	0	2	.60	.508
X7 Supervisors	225	0	1	.41	.493
X8 Tractor	225	0	10	.21	.755
Y-Loading Time	225	17	60	39.44	10.520
Valid N (listwise)	224				

Investments in specialised trucks (X4), front-end loaders (X6), and supervisors (X7) are very low, leaving much of the waste removal and loading done by hand by workers, thereby extending the loading time (Y) taken to clear a waste dump by a mean of 39.44 minutes. The role of supervisors (X7) is to monitor workers clearing and loading waste onto the skip when a specialised waste truck (X4) is available. Where a tractor-drawn trailer (X8) is used instead, front-end loaders (X6) load the trailer at those sites where such equipment is available. Often, workers load tractor-drawn trailers using shovels before moving on to the next waste dump.

### 3.2 Waste Operations at Interfaces

Using the stepwise option, a multiple regression analysis was carried out. Table 2 displays the results of multiple regression and correlation, while Figure 3 depicts a regression standardised residuals normal curve. Two models, 1 and 2, are generated: in model 1, a regression equation based on front-end loaders (X6) found a significant  $F(1,221) = 1093.23, 105.77, p .001$ , with an adjusted  $R^2$  of .040. In model 2, where loaders (X6) and tractors (X8) are combined, this produced a significant  $F(2,222) = 791.62, 104.04, p .001$ , with an adjusted  $R^2$  of .056. From the coefficients output, model 1

generates: loading time =  $47.138 - 39.004$  (loaders), while model 2 generates: loading time =  $41.747 - 4.187$  (loaders) +  $1.962$  (tractors). At a 95% confidence level, model 1 indicates a 40% variance explained by one predictor variable (X6), while model 2 indicates a 56% explained variance. But from the coefficients output, the p-column for X8 (Tractor) shows a value of .031, which is not statistically significant. Taking out variable X8 (Tractor) leaves only model 1 as the final model. For purposes of this study, we note that front-end loaders (X6) operate at several interfaces, indicating that these interfaces could provide intervention points for changing the operations of the solid waste chain. Hypothesis testing using Snedecor's F-test of overall significance applies in testing the null hypothesis.  $H_0$ : The null hypothesis ( $H_01$ ) states that the predictor variables in the regression do not have an effect on the model. We retrieve the results from the ANOVA output reported earlier. The results indicate F-values of 10.335 and 7.609 for models 1 and 2, respectively. In the model from the ANOVA output, the p-value in the sig. column is consistently less than the 0.05 significance level. The results indicate that we do not accept the null hypothesis. The alternative research hypothesis produces a better fit for the regression on the data.

Table 2  
 Multiple Regression Output for Loading Time in SPSS

Variables Entered/Removed <sup>a</sup>			
Model	Variables Entered	Variables Removed	Method
1	X6 Loaders	.	Stepwise (Criteria: Probability-of-F-to-enter <= .050, Probability-of-F-to-remove >= .100).
2	X8Tractor	.	Stepwise (Criteria: Probability-of-F-to-enter <= .050, Probability-of-F-to-remove >= .100).

a. Dependent Variable: Y-Loading Time

Model Summary <sup>c</sup>				
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.211 <sup>a</sup>	.044	.040	10.285
2	.254 <sup>b</sup>	.064	.056	10.200

a. Predictors: (Constant), X6 Loaders

b. Predictors: (Constant), X6 Loaders, X8Tractor

c. Dependent Variable: Y-Loading Time

		ANOVA <sup>a</sup>				
Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	1093.233	1	1093.233	10.335	.001 <sup>b</sup>
	Residual	23483.012	222	105.779		
	Total	24576.246	223			
2	Regression	1583.245	2	791.622	7.609	.001 <sup>c</sup>
	Residual	22993.001	221	104.041		
	Total	24576.246	223			

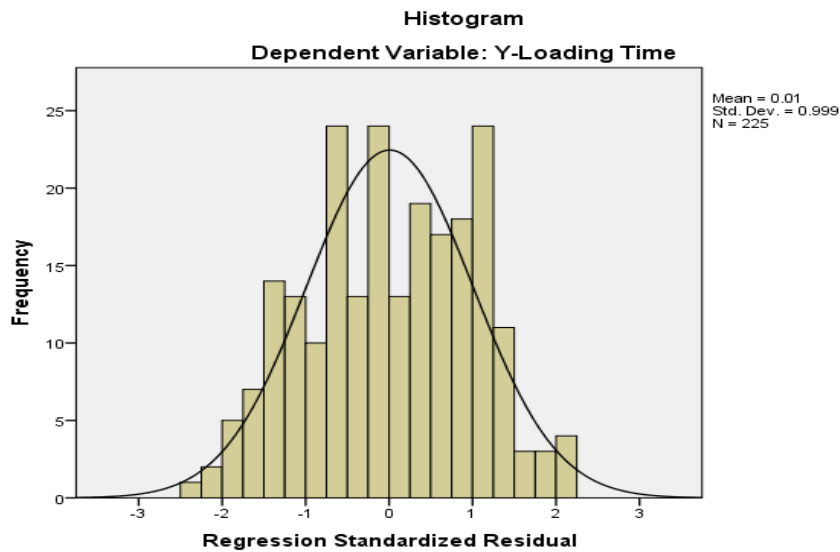
a. Dependent Variable: Y-Loading Time

b. Predictors: (Constant), X6 Loaders

c. Predictors: (Constant), X6 Loaders, X8Tractor

		Coefficients						
		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B	
		B	Std. Error	Beta			Lower Bound	Upper Bound
1	(Constant)	41.995	1.067		39.353	.000	39.892	44.098
	X6 Loaders	-4.355	1.355	-.211	-3.215	.001	-7.025	-1.685
2	(Constant)	41.474	1.085		38.214	.000	39.335	43.613
	X6 Loaders	-4.187	1.346	-.203	-3.112	.002	-6.839	-1.535
	X8Tractor	1.962	.904	.141	2.170	.031	.180	3.744

Figure 3  
 Histogram of Regression Standardized Residuals



### 3.3 Constraints in the Solid Waste Stream

With reference to imbedded constraints that limit the operations of the waste stream, several issues are noted. Firstly, illegal waste dumping, limited access to specialised waste trucks, spillage, and littering around bulk metal skips remain key challenges. Secondly, in the absence of adequate supervision, time is wasted clearing and loading waste. Experimental results in Table 3 show that increasing the number of waste pickers and the frequency of collection per week did not have a major effect on loading time (37.18). In cycle three, treatment loadings on X4 and X7 trigger a noticeable downward trend in loading time (31.07),

while with the addition of X8 in cycle 4, loading time drops to 26.10 minutes. These results show that equipment and supervision present opportunities for improving loading time. Thirdly, in the absence of sorting at the source, there are no transfer stations for re-routing waste away from final landfilling. Fourthly, most landfills do not meet the minimum engineering specifications as per government guidelines. Fifthly, annual budget allocations for waste management are generally insufficient, limiting the procurement of suitable equipment and vehicles. Overall, there is no evidence of efforts towards a circular economy.

Table 3

*Experimental Results on Treatment Effects*

Cycle	X1 Collection	X2 Workers	X4 Trucks	X6 Loaders	X7 Supervisors	X8 Tractor	Y- Loading time (in minutes)
1	-	-	-	-	-	-	39.44
2	X	X	-	-	-	-	37.18
3	-	-	X	-	X	-	31.07
4	-	-	-	X	-	X	26.10

Where X=treatment, - =conditions left as the earlier cycle

### 4. Discussion

The results reported with respect to objectives (i), (ii), and (iii) have highlighted bottlenecks in the operations of the solid waste stream. From the predictor variables generated through stepwise regression, several variables that operate at interfaces are of immediate interest: Y-Loading Time Front-end loaders (X7) and tractor-drawn trailers (X8) operate at interface A, that is, waste collection and loading for onward transmission. Improvements should address the rate of waste collection and the average time waste remains at a site before it is collected. Experimental results indicate a reduction in loading time following treatments on a set of independent variables. The number of workers at a site is important only if it is tied to the expected volume of waste. In order to reduce the actual time spent clearing a site and loading waste, two underlying factors come into play: specialised waste trucks and bulk

skips. Here, workers fill the skip by collecting all waste outside, and the truck hosts the skip and moves on. Where there is no skip or specialised truck, a front-end loader is used to assemble the waste and load it onto a tractor-drawn trailer. The critical issue is not the number of workers on site but the truck, tractor-trailer, or front-end loader arriving on time and on site. It is therefore possible to reduce loading time without increasing the number of workers. This requires that supervisors be present at a site and effective. For collection frequency, this is normally predetermined at the level of municipal management and is informed by the specific land use where the waste site is located. Commercial, industrial, and high-income residential districts are normally allocated three to four collections per week. Predominantly low-income, high-density residential districts score lower frequencies of waste

collection. Increasing the frequency per week for such areas may not be economical since they are, in general, associated with low per capita waste generation. Setting up a centralised and strategic waste treatment facility along the waste route to the landfill could address this because all waste would be assembled from various sites at such a facility, sorted, and distributed accordingly. This would have an immediate cost benefit in terms of lower waste volumes transported to the landfill and lower fuel costs per vehicle. In addition, almost all waste recovery activities would take place at this central facility. At interfaces B and C (Fig. 1), these interventions should have an immediate downstream impact on waste flows to the landfill site. At interfaces D, E, and F, it is possible to reduce waste volumes further by stockpiling all construction debris for future use (Huang et al., 2018). The proposed interface methodology requires that waste workers understand these linkages for interventions to have a cumulative effect (Hitomi, 2017), ultimately improving performance. Critical to the success of the interface method is the central role of waste information (Deus et al., 2017), without which it becomes difficult to trace impacts across interfaces. Access to waste data (Godfrey et al., 2012a, 2012b) makes it possible to keep a record of waste handled at every stage. This allows for measurement of various operations through time (Zaccariello et al., 2017) and across different municipalities. From the results, the need to improve the management staff and waste handling equipment remains a key challenge (Hristovski et al., 2010). Departing from looking at the waste stream from an integrated systems approach (Filho et al., 2016), the interface method instead calls for the waste stream to be mapped and segmented into phases, from collection to final disposal. The activities, processes, concerns, and inputs at each of the interfaces and the consequent outputs that feed into the next interface are broken down and analysed. In this way, the interface presents an opportunity space for initiating interventions focused on triggering a ripple effect downstream of the particular interface. It provides the means to manipulate inputs, hold others unchanged, and observe effects. In short, the interface method is not an exclusive stand-alone experiment; rather, it provides

opportunities for the creative management of waste under conditions of increasing generation per capita spurred on by greater rates of urbanisation (Loukil & Rouached, 2020). The waste management system is integrated, but the method proposed here does not threaten this coherence. Instead, it presents an alternative approach to improving the operations of the waste system. In the process, it generates information that could impact waste management in general (Oduro-Appiah et al., 2017). It would also feed into environmental protection and sustainable urbanisation.

## **5. Conclusion**

This paper presents an analysis of the performance of the municipal solid waste chain in terms of linear phases separated by interfaces and built within the umbrella of systems theory. Typical waste streams have indicated inadequacies with regard to specialised vehicles and equipment for waste handling. Analysis of waste operations at interfaces has highlighted challenges around supervision of waste workers and inefficiencies in waste collection. Imbedded limitations centre on compliance issues, the absence of sorting at the source, inadequate waste infrastructure, and constrained budget support. An experiment with four cycles of treatment on a sample of 29 sites was then carried out to test the outcomes of treatment effects. The results indicate a consistent reduction in loading time. Finally, an alternative approach to waste handling and management in the form of an interface-focused method is proposed for improving performance. The novelty of the study is in the use of a systems approach to deliver an interactive, multi-phase intervention. The scheme developed presents a flexible platform. This can improve the technical and managerial efficiency of solid waste handling.

## **6. Recommendations**

For waste management in urban areas in South Africa and the rest of Sub-Saharan Africa, it is necessary to initiate waste sorting at the source as a mandatory requirement for all waste generators. This could be achieved through the design of a flexible incentive scheme tied to rate payments for waste collection.

## 7. Funding Statement

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## 8. Conflict of Interest

The authors declare no conflict of interest in the publication of this paper.

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