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## Article

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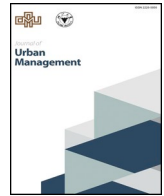
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# An optimisation approach to road sanitation workforce planning using differential evolution



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## ABSTRACT

At present, labour unions of waste disposal agencies and company management are at loggerheads, frequently turning out contradictory sanitation assessments. This reveals a shifting outlook of sanitation accomplishment that should be resolved. Unfortunately, there is scanty research on road sanitation and no study exists on how to determine the important workforce variables of these workers. To solve this research problem, a multi-objective optimisation model is developed and solved using the differential evolution model. The proposed model considered different constraints including workforce size, budgets, and service time. Three conflicting goals of maximization of cleanliness, maximization of workers' effectiveness and minimization of traffic obstruction were incorporated into the model and solved using practical data from a waste disposal agency in a developing country. A key result shows that the system's average workers' turnover rate is 0.2472 while the system's average service failure rate is 0.2518. For each location, the system requires an average of eight workers per period. The worker's average quality of work done is 0.8552. The outcome of the work revealed the feasibility of the model application. It was concluded that the model serves as a basis to evaluate road sanitation workers and may be used for budgetary purposes.

## 1. Introduction

The objective of this study was to establish how the road sanitation workforce planning problem could be solved using a multi-objective optimisation model, and in particular, to introduce a unique optimisation solver, differential evolution algorithm, to solve a non-linear association among the road sanitation maintenance workforce variables. Besides, the work is informed by three objective functions of maximization of cleanliness (Amblee, 2015; Lockyer, 2003; Vos et al., 2019), maximization of worker's effectiveness (ISF-UTS & SNV, 2016) and minimization of traffic obstruction. Although road maintenance activities involving the maintenance of signs (i.e. regulatory, guides and warning), pavements (i.e. flexible, semi-rigid and rigid), bridges, paving, drainages, cutting and filling of slopes have been established and examined in previous studies (Agarwal et al., 2017; Chen et al., 2020; Conreras-Nieto et al., 2019; Issa & Abu-Eisheh, 2017; Mansour et al., 2019), there is a paucity of contributions to uncover knowledge on road sanitation maintenance in the developing country's context. The wide subject of road maintenance has received interest, such as emergency maintenance (Sramek et al., 2019; Yau et al., 2014), periodic maintenance, routine maintenance and optimisation (Zhang & Gao,

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2012) but tailoring these maintenance types to the cleanliness of signs, fixtures, plantings, guard rails and elevations to support road infrastructural loads are not the focus of that interest. Instead, the World Health Organisation (WHO) has been focusing on poor sanitation issues as they affect urban poverty and health challenges.

As road management agencies receive increased complaints from road users concerning damages imposed on their vehicles as a result of poor sanitation and coupled with the stringent requirements to perform excellently, the pressure to maintain good sanitation services on roads has increased (Weststrate et al., 2019). The findings of this study will contribute greatly to reducing the operational cost of vehicles by offering first-rate road running surfaces considering that road sanitation plays a crucial role in reducing the acuteness and influence of sanitation on road users (Owusu, 2010). With information relating to road sanitation workforce planning optimisation, gaining insight into the workforce plans for sanitary workers is advantageous to waste managers since sanitary issues have the potential to influence the efficiency of the waste agency and the promotion of the goodwill for the organisation; even the potential to evade liability claims arising from poor sanitation practices will be actualized (Mason et al., 1998; Linard et al., 1999; Conradie & Joubert, 2004; Eitzen et al., 2004; Pastor & Corominas, 2010; Corominas et al., 2012; den Bergh et al., 2013; Harper, Kleinman, Gallagher, & Knight, 2013; Jennings & Shah, 2014; Ighravwe & Oke, 2014; Jennings & Shah, 2014; Ighravwe et al., 2019, 2016; Mei et al., 2016; Mei et al., 2016; Simeunović et al., 2017).

The insightful studies across developing countries are the growing evidence to reveal the negative impacts of sanitation and the need to take it more seriously (Zimbabwe – Chinyama et al., 2012; India – Sahoo et al., 2015; Ghana and Ethiopia – Grocker et al., 2017; East Africa – Tsinda et al., 2015; Eastern Zambia – Bardosh, 2015; Thailand – Pranee, 2015). Other studies include Conradie and Joubert (2004), Corominas et al. (2012), Jenning and Shah (2014), Simeunovic et al. (2017). More recently, a group of studies (Ighravwe & Oke, 2014; Ighravwe et al., 2016, 2019) advocate for a change in the knowledge domain of workforce planning. It is therefore sensible to address this gap and respond to the call by proposing and testing a multi-objective model of road sanitation with a particular interest in the workforce planning scheme of developing countries. Consequently, this paper will address the gap by elaborating through the formation of the problem as a non-linear multi-objective structure and then solving it with the classical differential evolution scheme. This will add to the present knowledge bank and extend to theoretical knowledge relating to road sanitation. The outcome of this research is potentially useful and is important to waste disposal management, works managers and engineers in waste disposal agencies because they may offer understanding to many issues.

Previous studies on road sanitation have explained road infrastructure maintenance through the quantitative lens of neural networks (Marovic et al., 2018), and dynamic programming (Ma et al., 2018), they fail to take advantage of solving the road maintenance problem in the presence of conflicting objectives. The outstanding advantages of being straightforward, likelihood to adjust favourites, the choice of only optimal points or visualizing the larger perspective (using Pareto) have not been exploited. (Xiao et al., 2007; Mavrotas, 2009; Trzaskalik et al., 2011; Fazlollahi et al., 2012; de Meyer et al., 2015). This paper fills that research and practice gap. This study organizes the remaining sections as follows: Section 2 presents mathematical expressions used to optimize road maintenance workforce parameters. Section 3 presents a case study used to evaluate the proposed model's performance. Section 4 contains the concluding remarks of this study.

## 2. Proposed model

During the literature survey carried out for this study, it was discovered that there is hardly any alternative model available in literature to tackle the work planning problem. Hence it is challenging to benchmark the performance of the model against some other existing models. The proposed method in this work, differential evolution, is a novel analytical method that optimized the road sanitation problem through iterations, attempting to enhance a candidate's solution concerning a specific degree of quality. This study uses a differential evolution method in the road sanitation problem with the following advantages. First, the differential evolution will permit the researcher to search for the accurate global minimum from a multi-modal exploration space irrespective of the primary parameter values. Furthermore, it exhibits fast convergence and also utilizes little control parameter. It is interesting to note that though the model solve the sanitation workforce problem, there is potential to adapt to similar settings in other sector. This is because the model has a general framework that is easily adaptable to systems.

### 2.1. Model formulation

The proposed model is developed because existing multi-objective optimisation model cannot generate workforce plan under traffic obstruction consideration. The model is developed to address the following issues:

- Determination of the expected workforce per period.
- Provision of insights on workers expected at a duty post.
- Design of a bonus scheme based on the quality of work done.
- Evaluation of workforce deployment strategy effectiveness based on failure rate.
- Development of a workforce back-up plan for workers shortage based on turnover rate.

The proposed model is formulated based on the following assumptions:

- The maximum and the minimum number of workers for each road is known.
- The service time for each worker is known.

- Overtime activities are monetized.
- The maximum and minimum quality of work done by the workers for each road is known.
- Staff are employed on a full-time basis.

The indices and decision variables nomenclature used to develop the proposed model are:

Indices			
$i$	index of route, $i = 1, 2, \dots, m$	$t$	index of period, $t = 1, 2, \dots, T$
$l$	index of location, $l = 1, 2, \dots, n$		
Decision variables			
$x_{ilt}$	maintenance workforce size in location $l$ that belongs to route $i$ during period $t$ .	$R_{ijt}$	workers' recruitment rate in location $l$ that belongs to route $i$ during period $t$ .
$e_{ijt}$	expected workload in location $l$ that belongs to route $i$ during period $t$ .	$t_{ijt}$	workers turnover rate in location $l$ that belongs to route $i$ during period $t$ .
$f_{ilt}$	service failure rate of a maintenance worker in location $l$ that belongs to route $i$ during period $t$ .	$t_{ilt}$	Worker turnover rate of a maintenance worker in location $l$ that belongs to route $i$ during period $t$ .
$s_{ilt}$	service delivery rate of a maintenance worker in location $l$ that belongs to route $i$ during period $t$ .	$Q_{ilt}$	Service quality a worker in location $l$ that belongs to route $i$ during period $t$ .

In the proposed model, Equations (1)–(3) give the mathematical expressions for the model's objective function. Here, Equation (1) gives the expression for street cleanliness, while Equation (2) gives the expression for workers' service failure rate with respect to assigned service time. Equation (3) defines the expression of the impacts of road maintenance on traffic obstruction (Equation (3)).

$$\text{Max } f_1 = \sum_{t=1}^T \sum_{i=1}^n \sum_{l=1}^m \{Q_{ilt} S_{ilt}\} \tag{1}$$

$$\text{Min } f_2 = \sum_{i=1}^m \frac{1}{T} \left\{ \sum_{t=1}^T \sum_{l=1}^n \frac{f_{ilt} x_{ilt}}{S_{ilt} x_{ilt}} \right\} \tag{2}$$

$$\text{Max } f_3 = \sum_{t=1}^T \sum_{i=1}^m \left\{ \bar{T}_{ilt} - \sum_{l=1}^n \{O_{ilt}\} \right\} \tag{3}$$

$$O_{ilt} = \begin{cases} 0 & \text{if } s_{ilt} = 0 \\ \alpha_{ilt} s_{ilt} & \text{Otherwise} \end{cases} \tag{4}$$

where,  $\alpha_{ilt}$  denotes the rate of traffic obstruction for a worker in location  $l$  that belongs to route  $i$  during period  $t$ .

To account for the workloads in a street, Equation (5) is used to establish the relationship between the expected service rates and their service failure rates is considered. In addition, the relationship between workers' turnover and recruitment rates is considered as another constraint for this workforce-sizing problem (Equation (6)).

$$S_l^{\min} \leq \sum_{i=1}^n \{s_{ilt} + f_{ilt}\} x_{ilt} \leq S_l^{\max} \quad \forall i, l, t \tag{5}$$

$$x_{ilt+1} = R_{ilt} (1 - t_{ilt}) x_{ilt} \quad \forall i, l, t \tag{6}$$

Given that the workers are only allowed to work within the first few hours in a day, the relationship between the total man-hour and the total working period per day is used to improve the workforce planning model (Equation (7)).

$$\frac{\sum_{i=1}^m \{s_{ilt} + f_{ilt}\} x_{ilt}}{\sum_{i=1}^m x_{ilt}} \leq H \quad \forall l, t \tag{7}$$

This study used Equation (8) to ensure that workers' recruitment rate is equal or greater than workers' turnover rate. Equations (9) and (10) are used to control the system's recruitment rate.

$$R_{ilt} \geq t_{ilt} \quad \forall i, l, t \tag{8}$$

$$R_{ijt} = \begin{cases} 1 & \text{if } w_{ilt} = w_{ilt+1} \\ 1 + R_{ijt} & \text{otherwise} \end{cases} \quad \forall i, l, t \tag{9}$$

$$\sum_{l=1}^m R_{ilt} = R_t^{\max} \quad \forall i, t \tag{10}$$

where,  $R_t^{\max}$  denotes the maximum recruitment rate in period  $t$ .

Equation (11) gives the expression for workforce availability per period. This expression depends on individual worker

availability. This study used Equation (12) to limit the total workforce in a location.

$$\sum_{i=1}^m \sum_{l=1}^n e_{ilt} x_{ilt} \geq A_t \quad \forall t \tag{11}$$

$$\sum_{i=1}^n x_{i|0} + \sum_{i=1}^n \sum_{t=1}^t x_{ilt} \leq x_i^{\max} \quad \forall j \tag{12}$$

where,  $e_{ilt}$  denotes the rate of a maintenance worker in location  $l$  that belongs to route  $i$  during period  $t$ ,  $A_t$  denotes the expected workforce availability in period  $t$ , and  $x_i^{\max}$  denotes total workforce for route  $i$ .

This study used Equation (13) to define the minimum service time required from the workers in a road maintenance company. Equation (14) gives the expression for the relationship between two periods.

$$\sum_{i=1}^m \sum_{l=1}^n \{s_{ilt} - f_{ilt}\} x_{ilt} - D_{ilt} \leq 0 \quad \forall t \tag{13}$$

$$D_{ilt} = (1 + e_{il}) D_{ilt-1} \quad \forall i, l, t \tag{14}$$

where,  $e_{il}$  denotes the service improvement rate in route  $l$  for workers  $i$ , and  $D_{ilt}$  denotes the minimum service time required from a worker in route  $l$  for workers  $i$  at period  $t$ .

This study used Equation (15) to control the periodic workforce expense. Equation (16) defines the expression for the set-covering constraint, while Equation (17) gives the expression for the non-negativity constraints.

$$\sum_{i=1}^m \sum_{l=1}^n (1 + d_{il}^1 + d_{il}^2) c_{il} x_{ilt} \leq B'_t \quad t > 1 \tag{15}$$

$$x_{ilt} \geq 1 \quad \forall i, l, t \tag{16}$$

$$w_{ijt}, f_{ijt}, s_{ijt}, t_{ijt} \geq 0 \quad \forall i, l, t \tag{17}$$

where,  $B'_t$  denotes total workforce budget for period  $t$ ,  $d_{il}^1$  and  $d_{il}^2$  denotes the proportion of training and contingency costs for a worker in route  $l$  for workers  $i$  at period  $t$ , and  $c_{il}$  denotes the unit basic cost for a worker in route  $l$  for workers  $i$ .

### 3. Case study

This study used a waste management company in the southwestern part of Nigeria as a case study. The organisation was established in 1977. It is responsible for the collection of waste in the municipals . The company has developed different landfill sites across the city to manage solid waste in the city. It has four maintenance workshops that provide engineering services to their field workers daily. As of 2018, the workforce size of this organisation is more than 5000 workers. During the proposed model application, we considered six planning periods. This study collected data sets from three locations; it considered two main road networks per location. Table 1 shows some of the collected data sets that were used to implement the model. To solve the formulated multi-objective model, we selected goal programming and different evaluation algorithm as solution methods. Ighravwe et al. (2019) presented the justification for using these methods to solve workforce planning multi-objective optimisation models. Their work also contains the detailed of the selected DE algorithm. This study uses 100 epochs as its stoppage criterion and a mutation and crossover probabilities of 0.3 and 0.5, respectively. Fig. 1 shows the DE algorithm convergence plot; this plot shows that the algorithm converged after 41 iterations.

#### 3.1. Workforce size

Table 2 shows the workforce size allocation at different periods. The selected locations require 1570 workers for six periods. Out of this value, Location 1 needs 506 workers, Location 2 needs 528 workers and Location 3 needs 528 workers. The period-wise

**Table 1**  
Model implementation parameters.

Parameters	L11	L12	L21	L22	L31	L32
Workers (min, max)	40, 50	30, 50	40, 50	30, 50	40, 50	25, 50
Turnover (min, max)	0.1, 0.4	0.1, 0.4	0.1, 0.4	0.1, 0.4	0.1, 0.4	0.1, 0.4
Failure (min, max)	0.2, 0.3	0.2, 0.3	0.15, 0.3	0.15, 0.3	0.1, 0.3	0.1, 0.3
Service (min, max)	5,10	5,10	4,10	5,10	4,10	5,10
Quality (min, max)	0.7	0.7	0.7	0.7	0.7	0.7
Salaries (N)	30,000	30,000	30,000	30,000	30,000	30,000
Service demand	2000	2000	2000	2000	2000	2000

Note: \$1 = N365.

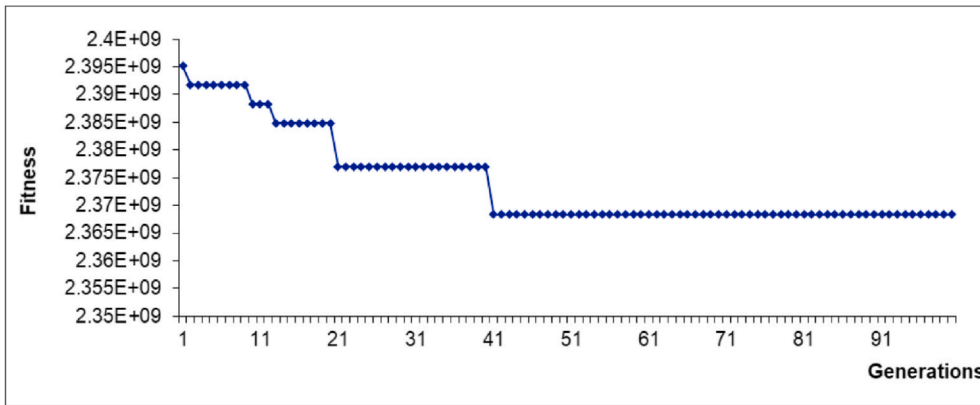


Fig. 1. DE algorithm convergence plot.

workforce requirement shows that Period 1 had the least workforce size (222 workers), while Period 3 had the highest workforce size (276 workers). The route-wise results show that Route 6 has the least maximum workforce (46 workers), while routes 1 and 2 have the same number of maximum, which is the highest required across the routes (Fig. 2). Routes 1 and 4 had least workers per period (40 workers), while routes 2 and 3 had the highest required workers per period (42 workers). Fig. 2 shows that the average number of workers required for routes 2 and 3 are the same (46 workers). Routes 5 and 6 required the same average workforce size (45 workers).

### 3.2. Workforce working periods

By combing the information in Tables 2 and 3, we observed that the case study requires 422,330 h of work per day. Period-wise comparison of periods 1 and 3 total working hours show that they are the same (46 h); this is also true for periods 4 and 6 total working hours (47 h). Routes 1, 3, 5, and 6 maximum working hours are the same (9 h) – see Table 3 for more details. This figure shows that routes 2 (8 h) and 4 (10 h) had the lowest and highest working hours, respectively. Routes 1 and 3 had the same minimum working hour (7 h), routes 2 and 5 had 5 h as their minimum working hours, and routes 4 and 6 had 6 h as their minimum working hours. Fig. 3 shows that the average working hours for the routes are the same (8 h).

### 3.3. Workforce quality of work done

Table 4 shows a period-wise of the quality of work done. Period 2 has the highest average quality of work done per period (0.9168). Period 4 has the least average quality of work done per period (0.8101). Fig. 4 shows that Route 5 (0.9922) has the highest maximum quality of work done, while Route 2 (0.8994) has the least maximum quality of work done. On the other hand, Route 6 (0.8247) has the highest minimum quality of work done, while Route 1 (0.7003) has the lowest minimum quality of work done. In terms of the routes’ average quality of work done, Route 5 (8837) has the highest value, while Route 3 (0.8136) has the lowest value (Fig. 4).

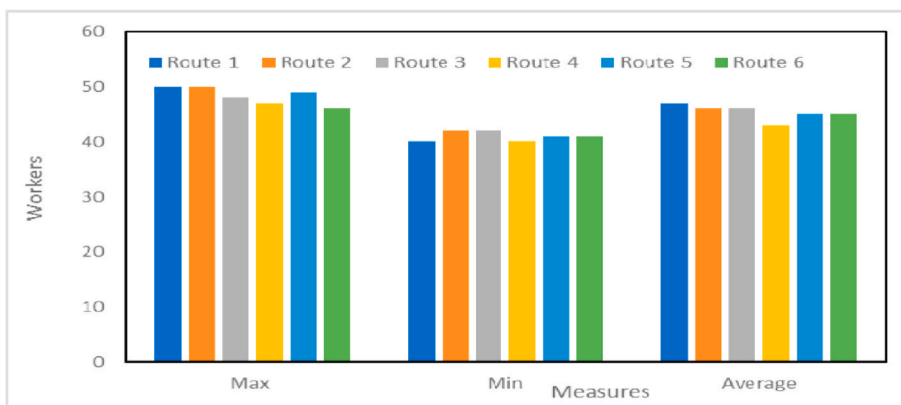


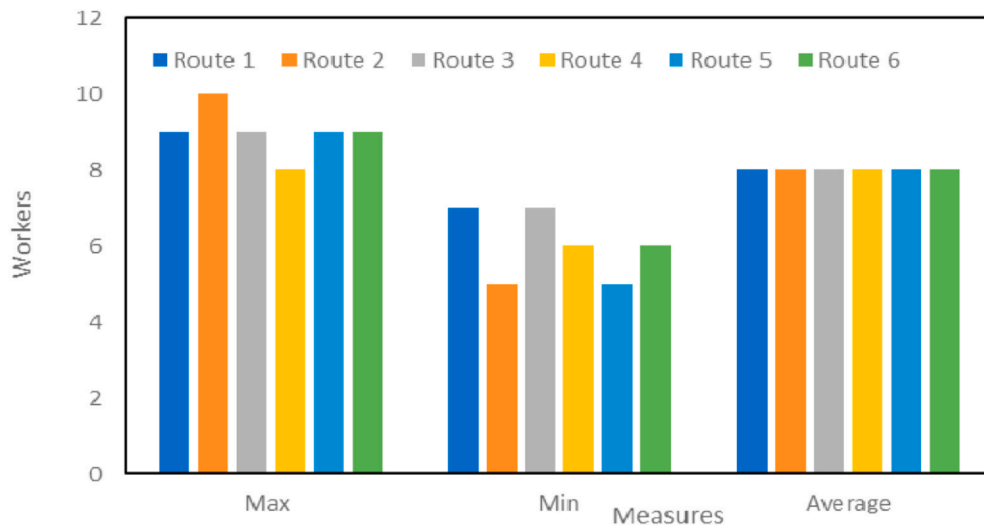
Fig. 2. The workforce plan statistics.

**Table 2**  
The locations workforce size.

	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
Route 1	45	49	50	49	40	43
Route 2	48	48	43	44	50	42
Route 3	44	47	48	45	45	42
Route 4	40	43	41	44	47	42
Route 5	49	42	48	46	41	44
Route 6	41	44	46	46	46	43

**Table 3**  
The workforce working hours.

	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
Route 1	7	7	7	9	7	7
Route 2	9	5	9	9	6	10
Route 3	7	9	8	9	7	7
Route 4	6	7	8	7	7	8
Route 5	8	9	5	7	7	8
Route 6	9	6	9	6	6	7



**Fig. 3.** The working hours statistics.

**Table 4**  
The quality of work done.

	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
Route 1	0.9035	0.9248	0.9674	0.7003	0.8010	0.9861
Route 2	0.8267	0.8994	0.7373	0.7746	0.8104	0.8772
Route 3	0.7047	0.8888	0.7959	0.8714	0.9189	0.7019
Route 4	0.8986	0.8393	0.7225	0.7594	0.9338	0.9435
Route 5	0.7834	0.9922	0.9580	0.9300	0.9058	0.7325
Route 6	0.8402	0.9560	0.8934	0.8247	0.8829	0.8992

### 3.4. Workforce service failure rate

From a period-wise perspective, Period 5 average service failure rate is 0.2504. This value represents the highest value among the planning periods (Table 5). Period 1 has the lowest average service failure rate (0.2189). In terms of the maximum service failure rate per period of a route, Route 4 has the highest values (0.2998), while Route 1 has the lowest value (0.2725). Fig. 5 shows that Routes 1 and 2 had the lowest and highest minimum service failure rate per period, respectively. This figure shows that routes 3 (0.2447) and 2 (0.2588) had the lowest and highest average service failure rates, respectively (see Table 6).

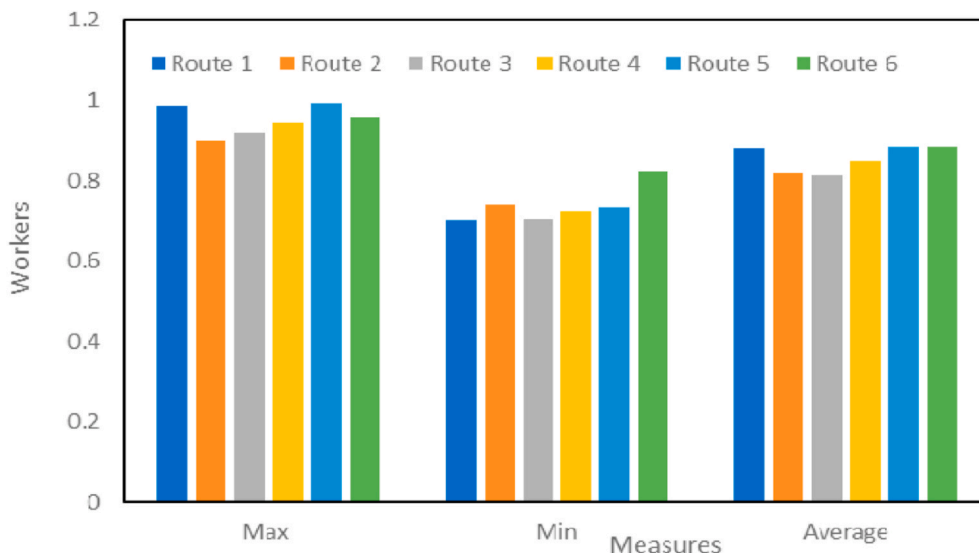


Fig. 4. The quality of work done statistics.

**Table 5**  
The locations' service failure rate.

	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
Route 1	0.2598	0.2719	0.2725	0.2720	0.2328	0.2009
Route 2	0.2959	0.2537	0.2233	0.2624	0.2704	0.2469
Route 3	0.2567	0.2529	0.2734	0.2202	0.2390	0.2262
Route 4	0.2500	0.2882	0.2079	0.2292	0.2589	0.2998
Route 5	0.2324	0.2881	0.2362	0.2222	0.2864	0.2109
Route 6	0.2784	0.2821	0.2802	0.2603	0.2151	0.2073

**Table 6**  
The workforce turnover rate.

	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
Route 1	0.3676	0.3104	0.2651	0.1157	0.1689	0.2152
Route 2	0.1824	0.3177	0.2957	0.3333	0.1634	0.2325
Route 3	0.1695	0.1634	0.1904	0.3491	0.1665	0.238
Route 4	0.3136	0.2786	0.2941	0.2613	0.3057	0.3065
Route 5	0.2748	0.3140	0.1958	0.1720	0.3004	0.1224
Route 6	0.1977	0.2599	0.1632	0.2399	0.3286	0.3263

3.5. Workforce turnover rate

Table 4 shows that Period 2 has the highest average workforce turnover rate (0.2740), while Route 3 has the lowest average workforce turnover rate (0.2341). Route 1 has the highest maximum workforce turnover rate (0.3676) and Route 4 has the lowest maximum workforce turnover (0.3136). Route 1 has the lowest minimum workforce turnover rate (0.1157), while Route 4 has the highest minimum workforce turnover (0.2613). Fig. 6 shows that the average workforce turnover rate for Route 2 has the highest value (0.2542), while Route 3 has the lowest value (0.2128).

3.6. Traffic obstruction rate

The period-wise results for traffic obstruction rate show that there will be more traffic obstruction in Period 5 than the other periods. On the contrary, there will be less traffic obstruction in Period 1 than the other periods (Table 7). Fig. 7 shows that the maximum traffic obstruction that occurs in locations 2 and 3 are the same. In terms of the minimum traffic obstruction rate per period, locations 1 and 2 have minimum and maximum values, respectively (Fig. 7). The results for the average traffic obstruction rate show that locations 1 and 3 had the minimum and maximum values, respectively.



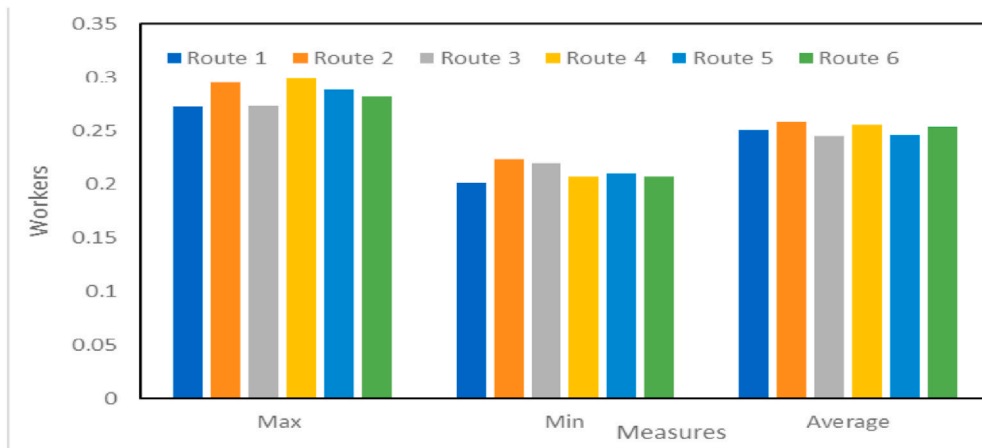


Fig. 5. The service failure rate statistics.

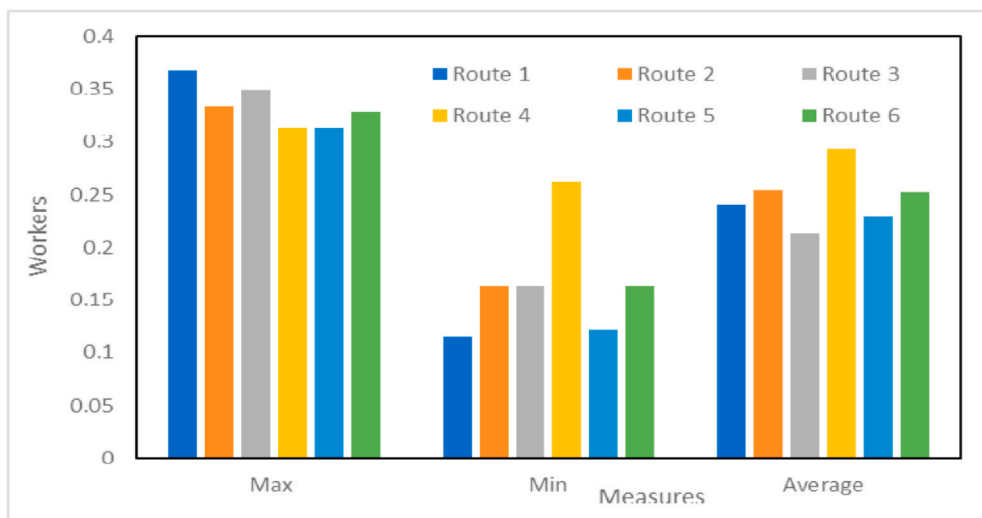


Fig. 6. The turnover rate statistics.

Table 7

Traffic obstruction rate for the selected locations.

	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
Location 1	0.0139	0.0172	0.0101	0.0158	0.0194	0.0132
Location 2	0.0115	0.0133	0.0113	0.0107	0.0198	0.0189
Location 3	0.0119	0.019	0.0198	0.0151	0.0137	0.0147

#### 4. Conclusions

This article has formulated a multi-objective optimisation model for road sanitation problem. It validated the model performance using practical data from a company in Nigeria. Solving the road sanitation problem is important for several reasons, especially the need to resolve the dispute in perceptions of what road sanitation performance means. Labour unions and company management frequently turn out contradictory sanitary assessments, revealing a shifting outlook of sanitation accomplishment (Munamati et al., 2018). This article has addressed the gap in providing a common basis for this assessment. Thus, this article's suggests that road sanitation workforce should be evaluated based on work content and workforce budget. It was found that under the conflicting objectives of cleanliness, traffic disruption and workers' effectiveness, a feasible set of solutions were attained. Despite emerging research to enhance road maintenance practices, more investigations are needed to build up new quantitative measures that will suitably and fairly assess the road sanitation workforce and eliminate the frequent contradictory sanitary assessments of road sanitary workers.

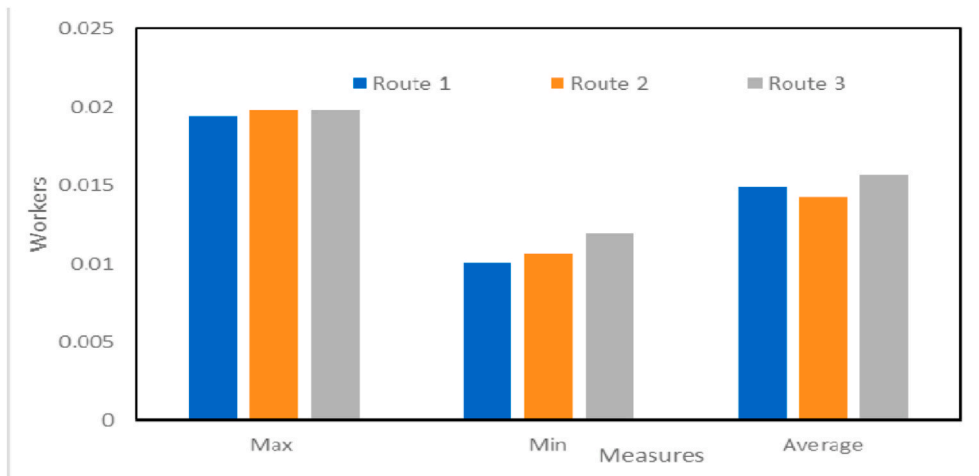


Fig. 7. The traffic obstruction rate statistics.

### Declaration of competing interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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