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A FRAMEWORK FOR APPLICATION OF GENETIC ALGORITHM IN PRODUCTIVITY OPTIMIZATION OF HIGHWAY EQUIPMENTS USING EVOLVER SOFTWARE

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ABSTRACT

Genetic algorithm is a tool to solve selection and optimization related problems. It is a heuristic search process which helps in optimizing productivity of highway equipments. This paper aims at developing an approach for optimizing productivity of hydraulic excavators and vibratory tandem steel drum rollers in highway projects using genetic algorithm. For analysis, EVOLVER 5.7- add-in software of excel has been used. It has been observed that for hydraulic excavators, the difference between actual productivity on site and the productivity as computed through productivity equation is about 7.9 % and the difference between the computed productivity and the optimized productivity is about 7.8 %. For vibratory steel drum rollers, the total optimized productivity as given by EVOLVER 5.7 software is about is about 15.69 % higher than the computed productivity. Also, excavator Volvo EC 210 BLC, and roller L&T 1107D appear to be more feasible to be deployed in the project.

KEYWORDS: Genetic algorithm; Optimization; Hydraulic excavators; Vibratory rollers; Evolver; Productivity.

INTRODUCTION

Construction of highway projects involves huge investments for deployment of highway construction equipments. So optimization of productivity of equipment is necessary for on-time availability, cost reduction and better performance. One of the very important equipment of highway construction is hydraulic excavators. It primarily helps in initial stage of highway construction particularly during cleaning and grubbing. This paper aims at optimizing the productivity of hydraulic excavators using genetic algorithm. Some of the major factors affecting the productivity of hydraulic excavators have been identified and the input data has been fed in an optimizing software EVOLVER, through which an optimal solution has been obtained.

Genetic algorithms are adaptive heuristic search algorithm premised on the Darwin's evolutionary ideas of natural selection and genetic evolution. The basic concept of genetic algorithms is designed to simulate processes in natural system necessary for evolution. As such they represent an intelligent exploitation of a random search within a defined search space to solve a problem. It generates solutions to optimization problems using techniques inspired by natural evolution, such as inheritance, mutation, selection, and crossover (Bajpai and Kumar 2008). Steps for the procedure of genetic algorithms are: (1) Defining a solution representation; (2) Setting the variables, objective functions and constraints; (3) Generating initial population of solutions; (4) Evaluating the population; and (5) Evolution cycles (Hegazy and Kassab, 2003).

The concept of a genetic algorithm based multi-objective approach, which utilizes a genetic search for simultaneously optimizing more than one variable i.e. time and cost (Zheng, et al. 2004). Jun and El-Rayes (2011) have developed a novel multiobjective optimization model to simultaneously optimize resource levelling and allocation for construction projects. The present model is designed to provide construction planners with new capabilities, including (1) maximizing resource utilization efficiency by directly measuring and minimizing undesirable resource fluctuation; (2) simultaneously minimizing project duration while complying with all resource availability constraints and (3) generating optimal trade-offs between minimizing project duration and maximizing resource utilization efficiency.

Two new metrics for resource levelling and a robust optimization model were developed to maximize the efficiency of resource utilization in construction projects. The model is designed to search for optimal and practical schedules that minimize undesirable resource fluctuation while simultaneously minimizing the resource peak demand (El-Rayes and Jun, 2009). Doulabi, et al. (2011) have introduced a novel hybrid genetic algorithm for resource levelling which takes advantage of activity splitting whenever possible. The proposed genetic algorithm is equipped with a novel local search heuristic and a repair mechanism. The repair mechanism is used to restore the feasibility of the solutions by fixing the precedence relations.

Genetic algorithm procedures converge quickly on optimal solutions after examining only a small fraction of the search space and have been applied successfully to complex optimization problems in engineering; XSOME, the computer-based program developed to solve the excavating and haulage equipment selection problem in opencast mining, has progressed from applying integer linear programming into developing a hybrid knowledge-based system and genetic algorithms (Haidar, et al. 1999). Hegazy (1999) has made three main developments with respect to improving the resource management of projects: (1) an effective improvement to resource allocation heuristics using random activity priorities; (2) a practical modification to resource leveling heuristics using a double-moment approach and (3) a multiobjective optimization of both resource allocation and leveling using the genetic algorithms technique.

CONCEPTUAL FRAMEWORK

Initial stage of highway construction is earthmoving operations and the first point to consider is that earthmoving productivity is governed by the excavator. All movement and functions of a hydraulic excavator are accomplished through the use of hydraulic fluid, with hydraulic cylinders and hydraulic motors. For the excavator system, the excavator is the prime mover and maximum prime output will be achieved if the excavator is working at maximum utilization and supplied with enough trucks. The regression model for actual productivity that has been undertaken and described in this paper has provided an equation that describes over 90% of the variance in a large set of data obtained from different sources and that provides a realistic estimate for the actual output for excavator earthmoving operations (Smith 1999). Formula to find out the productivity of a hydraulic excavator as given by Peurifoy and Schexnayder (2008) is expressed by the following relationship:

Productivity of hydraulic excavator (cum. / hr) =

$$\frac{3600 \text{ x Heaped capacity of bucket x Bucket fill factor x Height and swing factor}}{\text{Time cycle}} \text{ x } \frac{30}{60} \text{ x } \frac{1}{(1 + \text{Swell})} \quad (1)$$

Heaped capacity is expressed in cubic yard and time cycle is expressed in seconds.
Productivity of vibratory steel drum roller as mentioned in Peurifoy and Schexnayder (2008) is expressed as:
Productivity of vibratory steel drum roller (cum. / hr.) =

$$\frac{\text{Compacted width per roller pass x average roller speed x compacted lift thickness x efficiency}}{\text{No. of roller passes required}} \quad (2)$$

CASE STUDY

To analyze the optimum productivity of hydraulic excavators, two case studies are considered. The first case study (Case 1) is widening of Bhruch-Dahej highway (SH-06), Gujarat, India. Hydraulic excavators were used in initial stage of highway construction particularly in earthmoving operations. Collected primary data includes soil type, details of hydraulic excavators like heaped bucket capacity, maximum digging depth, swing angle, average depth of cut, working efficiency and cycle time. The models of hydraulic excavators used for excavation for Case 1 are L&T Komatsu PC 300-7 and JCB 3DX.
The details of the hydraulic excavators and soil type are tabulated in table 1 and the actual productivity of L & T Komatsu PC 300-7 is presented in Table 2.

Table 1: Details of hydraulic excavators and soil type (Case 1)

L&T Komatsu PC 300-7	Heaped bucket capacity	1.4 cum.	
	Max. digging depth	8.15 m	
	Swing angle	Varies from 75 to 180 degrees	
	Average depth of cut	3 m	
	Working efficiency	40 min. per hour	
	Cycle time	20 sec	Load Bucket- 6 Sec
			Swing with load- 6 Sec
			Dump load- 4 Sec
			Return swing- 4 Sec
JCB 3DX	Heaped bucket capacity	0.24 cum.	
	Max. digging depth	4.77 m	
	Swing angle	Varies from 60 to 120 degrees	
	Average depth of cut	1.5 m	
	Working efficiency	45 minutes per hour	
	Cycle time	19 Sec	Load Bucket- 7 Sec
			Swing with load- 5 Sec
			Dump load- 2 Sec
			Return swing- 5 Sec
Soil type	Clayey soil	Fill factor	100-110 %
	Wet or dry clayey soil	Swell	35%

Table 2: Actual production chart of L&T Komatsu PC 300-7

Sr. No.	Date	Hours per day	Excavation (cum.)
1	13.03.12	8	873
2	14.03.12	8	819
3	15.03.12	6	752
4	17.03.12	6	793
5	18.03.12	7	821
6	19.03.12	5	432
7	20.03.12	4	160
8	21.03.12	4	309
9	22.03.12	4	363
10	23.03.12	4	318
	TOTAL	56	5640
	Productivity (cum. / hr.)	100.71	

Similarly for JCB 3DX productivity in cum.per hour is 71.82.

The second case study (Case 2) for analysis is Ahmedabad-Viramgam-Maliya Road Project (AVMRP), Gujarat, India. This is also a widening project. Two different models of excavators used for earth moving operations for this case are TATA Hitachi EX 110 and Volvo EC 210 BLC. The details of the hydraulic excavators and soil type are tabulated in table 3 and the actual productivity of TATA Hitachi EX 110 is presented in table 4.

Table 3: Details of hydraulic excavators and soil type (Case 2)

TATA Hitachi EX 110	Heaped bucket capacity	0.9 cum.	
	Max. digging depth	4.72 m	
	Swing angle	Varies from 60 to 150 degrees	
	Average depth of cut	1.5 m	
	Working efficiency	42 min. per hour	
	Cycle time	21 sec	Load Bucket- 7 Sec
			Swing with load- 6 Sec
			Dump load- 4 Sec
			Return swing- 4 Sec
Volvo EC 210 BLC	Heaped bucket capacity	1.6 cum.	
	Max. digging depth	4.77 m	
	Swing angle	Varies from 60 to 120 degrees	
	Average depth of cut	6.7 m	
	Working efficiency	38 minutes per hour	
	Cycle time	21 Sec	Load Bucket- 6 Sec
			Swing with load- 6 Sec
			Dump load- 4 Sec
			Return swing- 5 Sec
Soil type	Earth rock mixture	Fill factor	100-110 %
	Wet or dry earth	Swell	35%

Table 4: Actual production chart of TATA Hitachi EX 110

Sr. No.	Date	Hours per day	Excavation (cum.)
1	05.04.12	6	489
2	06.04.12	5	452
3	07.04.12	6	512
4	09.04.12	3	283
5	10.04.12	4.5	392
6	11.04.12	4	400
7	12.04.12	4	378
8	13.04.12	5	459
9	14.04.12	3.5	259
10	15.04.12	3.5	243
	TOTAL	44.5	3867
	Productivity (cum./ hr)	86.90	

Similarly for Volvo EC 210 BLC productivity in cum.per hour is 138.5

The other category of equipment considered for this study is steel drum vibratory roller deployed in Case 1. The details of the production for model IR SD 110 is presented in table 5.

Table 5: Actual production of steel drum vibratory roller (IR SD 110)

Sr. No.	Date	Hours per day	Excavation (cum.)
1	27.05.12	2	468(subgrade)
2	28.05.12	2	3060 (embankment)
3	29.05.12	2	
4	30.05.12	1	
5	01.06.12	3	
6	04.06.12	1.5	384 (subgrade)
7	05.06.12	2	490 (embankment / subgrade)
8	06.06.12	2.5	510 (embankment)
9	07.06.12	3	420 (embankment)
10	08.06.12	1	315 (embankment)
	TOTAL	20	5647
	Productivity (cum./ hr)	282	

ANALYSIS

The actual productivity of excavators are affected by factors like (1) class of material (2) bucket capacity (3) height / depth of cut (4) angle of swing (5) cycle time (6) working efficiency and (7) skill of operator. Primary data pertaining to these parameters are tabulated in table 6. The productivity for all the four models of hydraulic excavators under consideration is calculated as per equation 1.

Table 6: Data affecting productivity and computation of productivity for hydraulic excavators (Case 1 and 2)

Description	L&T Komatsu PC 300-7	JCB 3DX	TATA Hitachi EX 110	Volvo EC 210 BLC	Total
Fill factor	1.05	1.05	1.1	1.1	
Swell (%)	35	35	25	25	
Heaped Bucket capacity (cum.)	1.4	0.75	0.9	1.6	
Max. Digging depth (m)	8.15	4.77	4.72	6.7	
Optimum height (m)	3.67	2.15	1.65	2.35	
% optimum depth	81.74	69.77	90.91	85.11	
Height-swing factor	0.82	0.95	0.99	0.98	
Efficiency factor	0.67	0.75	0.7	0.63	
cycle time (sec)	20	19	21	21	
Productivity (cum./ hr.)	107.68	78.75	94.09	149.02	429.54

Productivity shown in table 6 is based on computation as per equation (1). The other factors listed in the above table have been fed as input data to EVOLVER 5.7 software and carrying out trial runs the optimized productivity is obtained. Brief description of the process is as follows. For the model,
Objective function: Optimize the overall productivity

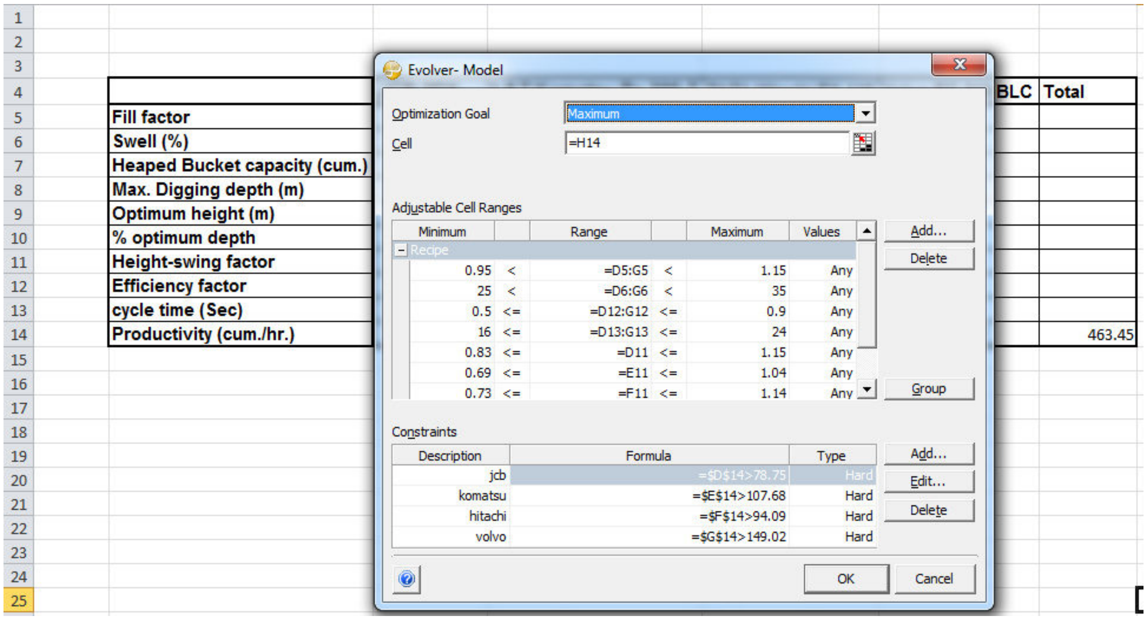
Adjustable cells:

Table 7: Details of adjustable cell ranges in EVOLVER model

Fill Factor	0.95 to 1.15
Swell (%)	25 to 35
Efficiency factor	0.5 to 0.9
Cycle time (sec)	16 to 24
Height-swing factor	0.83 to 1.15 (for JCB)
	0.69 to 1.04 (for L&T Komatsu)
	0.73 to 1.14 (for Tata Hitachi)
	0.69 to 1.12 (for Volvo)

Constraint:

Productivity of equipments should be more than the productivity obtained from formula.



Row	Item
5	Fill factor
6	Swell (%)
7	Heaped Bucket capacity (cum.)
8	Max. Digging depth (m)
9	Optimum height (m)
10	% optimum depth
11	Height-swing factor
12	Efficiency factor
13	cycle time (Sec)
14	Productivity (cum./hr.) 463.45

Optimization Goal: Maximum

Cell: =H14

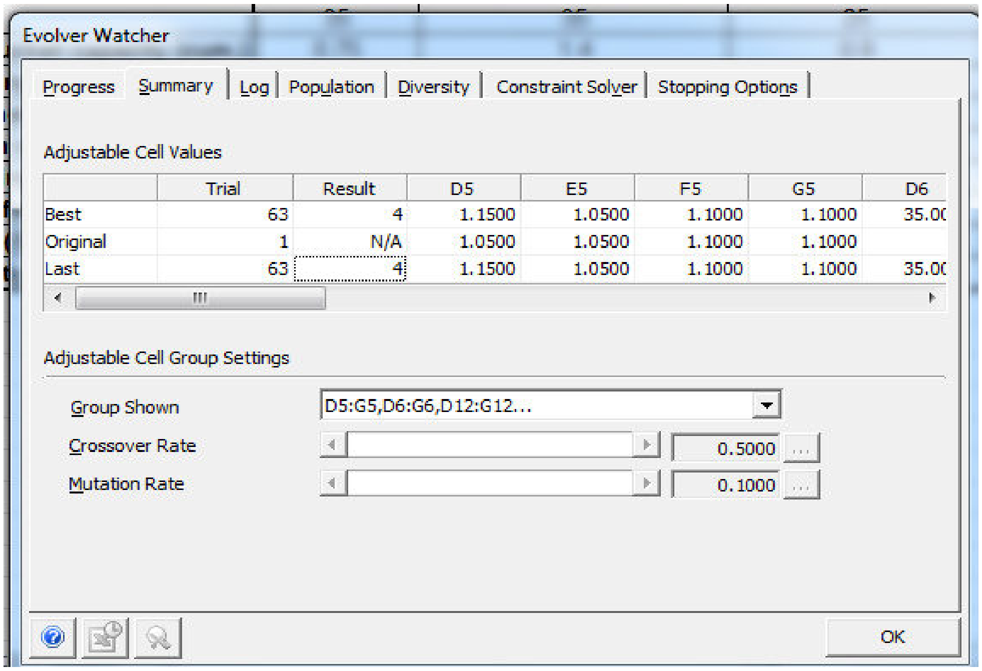
Adjustable Cell Ranges

Minimum		Range		Maximum	Values
Recipe					
0.95	<	=D5:G5	<	1.15	Any
25	<	=D6:G6	<	35	Any
0.5	<=	=D12:G12	<=	0.9	Any
16	<=	=D13:G13	<=	24	Any
0.83	<=	=D11	<=	1.15	Any
0.69	<=	=E11	<=	1.04	Any
0.73	<=	=F11	<=	1.14	Any

Constraints

Description	Formula	Type
jcb	=$D$14>78.75	Hard
komatsu	=$E$14>107.68	Hard
hitachi	=$F$14>94.09	Hard
volvo	=$G$14>149.02	Hard

Figure 1: Screen display for optimization goal, adjustable cell ranges and constraints of EVOLVER Model



Adjustable Cell Values

	Trial	Result	D5	E5	F5	G5	D6
Best	63	4	1.1500	1.0500	1.1000	1.1000	35.0
Original	1	N/A	1.0500	1.0500	1.1000	1.1000	
Last	63	4	1.1500	1.0500	1.1000	1.1000	35.0

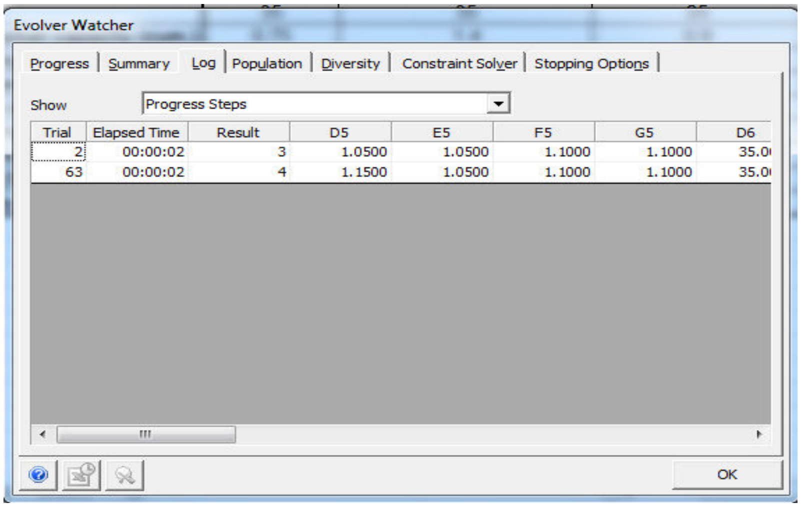
Adjustable Cell Group Settings

Group Shown: D5:G5,D6:G6,D12:G12...

Crossover Rate: 0.5000

Mutation Rate: 0.1000

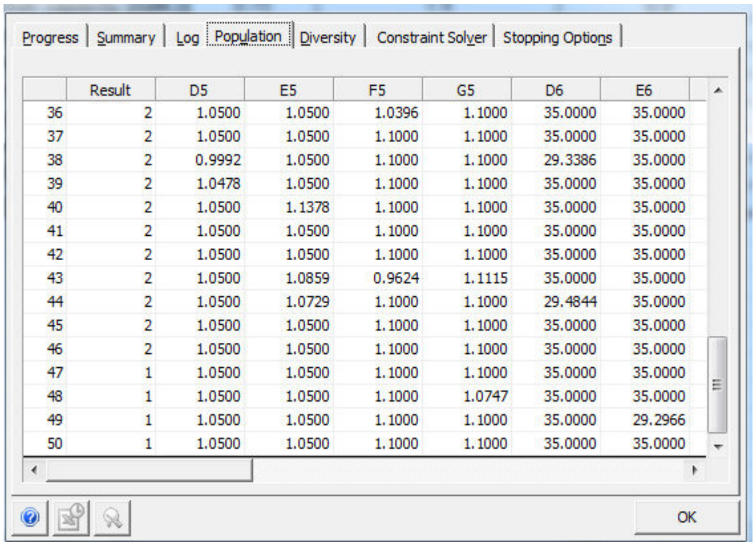
Figure 2: Screen display for EVOLVER Watcher showing crossover and mutation rate



Show: Progress Steps

Trial	Elapsed Time	Result	D5	E5	F5	G5	D6
2	00:00:02	3	1.0500	1.0500	1.1000	1.1000	35.0
63	00:00:02	4	1.1500	1.0500	1.1000	1.1000	35.0

Figure 3: Screen display for EVOLVER Watcher showing number of trials or iterations equal to 63



	Result	D5	E5	F5	G5	D6	E6
36	2	1.0500	1.0500	1.0396	1.1000	35.0000	35.0000
37	2	1.0500	1.0500	1.1000	1.1000	35.0000	35.0000
38	2	0.9992	1.0500	1.1000	1.1000	29.3386	35.0000
39	2	1.0478	1.0500	1.1000	1.1000	35.0000	35.0000
40	2	1.0500	1.1378	1.1000	1.1000	35.0000	35.0000
41	2	1.0500	1.0500	1.1000	1.1000	35.0000	35.0000
42	2	1.0500	1.0500	1.1000	1.1000	35.0000	35.0000
43	2	1.0500	1.0859	0.9624	1.1115	35.0000	35.0000
44	2	1.0500	1.0729	1.1000	1.1000	29.4844	35.0000
45	2	1.0500	1.0500	1.1000	1.1000	35.0000	35.0000
46	2	1.0500	1.0500	1.1000	1.1000	35.0000	35.0000
47	1	1.0500	1.0500	1.1000	1.1000	35.0000	35.0000
48	1	1.0500	1.0500	1.1000	1.0747	35.0000	35.0000
49	1	1.0500	1.0500	1.1000	1.1000	35.0000	29.2966
50	1	1.0500	1.0500	1.1000	1.1000	35.0000	35.0000

Figure 4: Screen display showing the population size 50

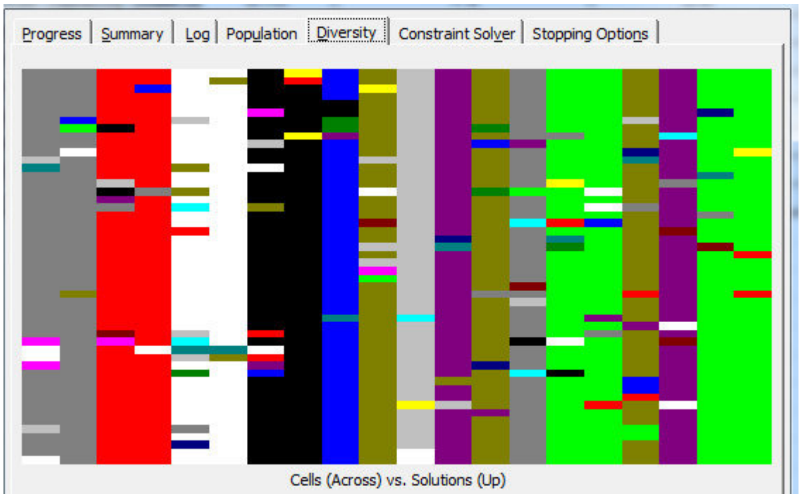
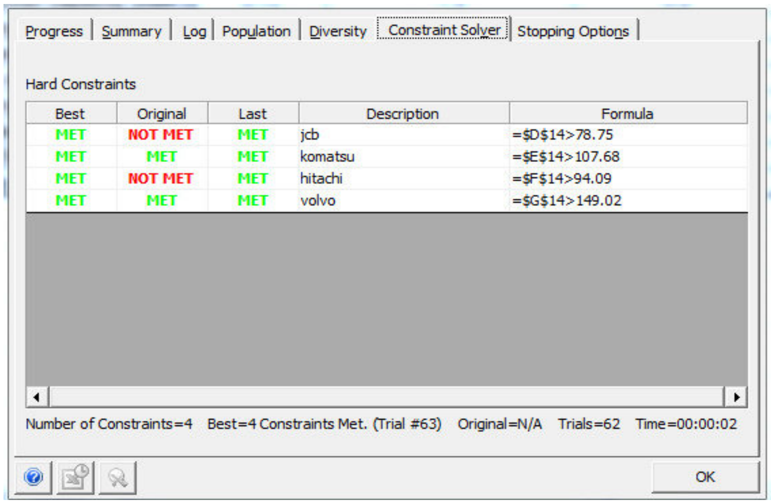


Figure 5: Screen display showing diversity pattern at predefined crossover and mutation rate



Hard Constraints

Best	Original	Last	Description	Formula
MET	NOT MET	MET	jcb	=$D$14>78.75
MET	MET	MET	komatsu	=$E$14>107.68
MET	NOT MET	MET	hitachi	=$F$14>94.09
MET	MET	MET	volvo	=$G$14>149.02

Number of Constraints=4 Best=4 Constraints Met. (Trial #63) Original=N/A Trials=62 Time=00:00:02

Figure 6: Screen display showing constraint solver and hard constraints

Results

Final result after completing the genetic algorithm optimization process is presented in table 8

Table 8: Optimized productivity for hydraulic excavators (Case 1 and Case 2)

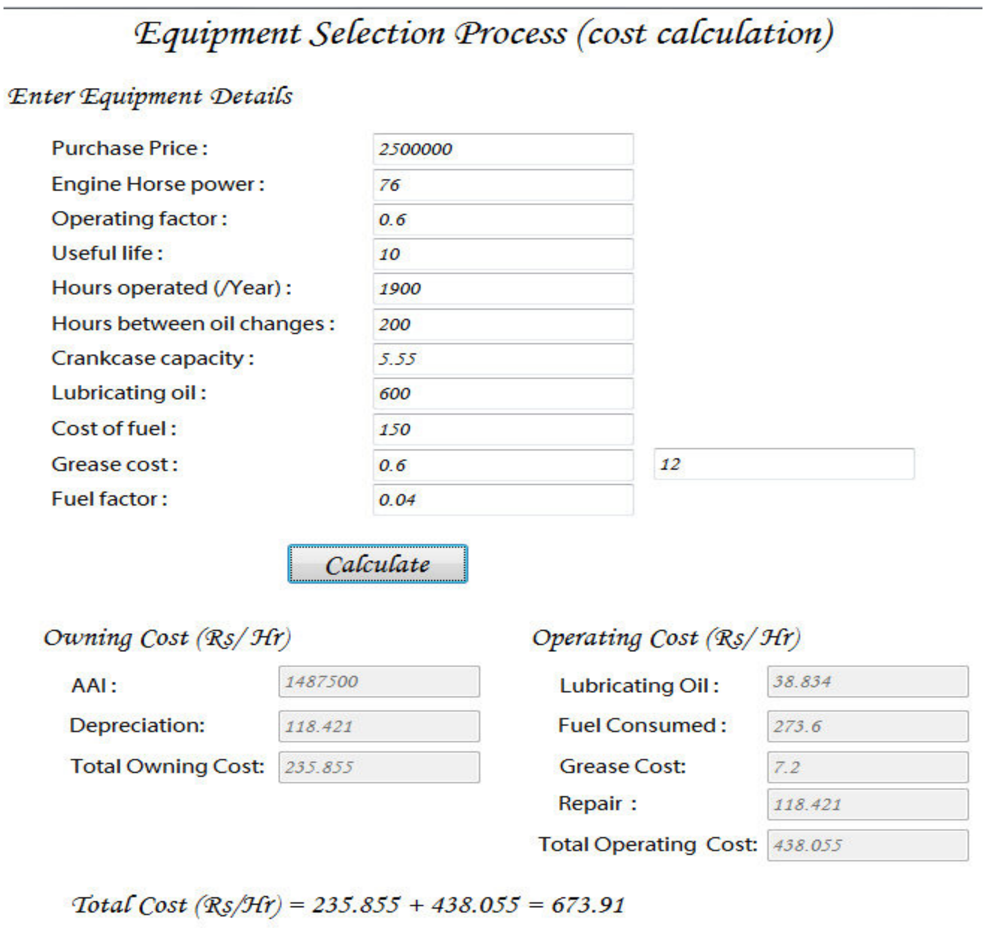
Description	L&T Komatsu PC 300-7	JCB 3DX	TATA Hitachi EX 110	Volvo EC 210 BLC	Total
Fill factor	1.05	1.15	1.1	1.1	
Swell (%)	35	35	25	25	
Heaped Bucket capacity (cum.)	1.4	0.75	0.9	1.6	
Max. Digging depth (m)	8.15	4.77	4.72	6.7	
Optimum height (m)	3.67	2.15	1.65	2.35	
% optimum depth	81.74	69.77	90.91	85.11	
Height-swing factor	0.82	0.95	0.99	0.98	
Efficiency factor	0.67	0.75	0.89	0.63	
cycle time (sec)	20	19	21	21	
Productivity (cum./ hr.)	107.68	86.25	120.49	149.02	463.45

The comparison of the actual productivity on site, productivity based on equation (1) and the productivity as obtained after optimization using genetic algorithm and EVOLVER 5.7 software is presented in table 9.

Table 9: Productivity comparison chart for hydraulic excavators (Case 1 and 2)

Description	Actual productivity on site (cum./ hr.)	Productivity based on equation (1) (cum./ hr.)	Productivity after optimization using genetic algorithm (cum./ hr.)
L&T Komatsu PC 300-7	100.71	107.68	107.68
JCB 3DX	71.82	78.75	86.25
TATA Hitachi EX 110	86.9	94.09	120.49
Volvo EC 210 BLC	138.5	149.02	149.02
Total	397.93	429.54	463.45

To facilitate the equipment selection process, the owning and operating cost of each of the models of the hydraulic excavators has been calculated using the software package developed by us. A sample computation of the owning and operating cost of JCB 3DX is presented in figure 7.



Equipment Selection Process (cost calculation)

Enter Equipment Details

Purchase Price : 2500000
Engine Horse power : 76
Operating factor : 0.6
Useful life : 10
Hours operated (/Year) : 1900
Hours between oil changes : 200
Crankcase capacity : 5.55
Lubricating oil : 600
Cost of fuel : 150
Grease cost : 0.6 12
Fuel factor : 0.04

Owning Cost (Rs/ Hr)

AAI : 1487500
Depreciation: 118.421
Total Owning Cost: 235.855

Operating Cost (Rs/ Hr)

Lubricating Oil : 38.834
Fuel Consumed : 273.6
Grease Cost: 7.2
Repair : 118.421
Total Operating Cost: 438.055

Total Cost (Rs/Hr) = 235.855 + 438.055 = 673.91

Figure 7: Screen shot of the package developed for computing equipment owning & operating cost (JCB 3DX)

The comparative owning and operating cost analysis for the models of hydraulic excavators like L&T Komatsu PC 300-7, JCB 3DX, TATA Hitachi Ex 110 and Volvo EC 210 BLC are presented in table 10

Table 10: Comparative analysis of owning and operating costs for hydraulic excavators (Case 1 and 2)

Model	Total cost (Rs./hr.)
L&T Komatsu PC 300-7	1020
JCB 3DX	674
TATA Hitachi EX 110	726
Volvo EC 210 BLC	865

To analyze the optimum productivity of vibratory steel drum rollers, the hard factors considered for study that affect the productivity include (i) compacted width per roller pass (ii) average roller speed (iii) compacted lift thickness (iv) number of roller passes required and (v) efficiency.

Productivity as computed by incorporating the values of the factors in the productivity formulae (2), is presented in table 11.

Table 11: Data affecting productivity and computation of productivity for vibratory steel drum rollers (Case 1 and 2)

Factor description	Models			
	L&T 1107D	IR –SD 110	DYNAPAC CA 150D	Total productivity (cum. / hr.)
Maximum operating weight (tones)	11.3	10.8	9.3	
Compacted width per roller pass (m)	2.3	2.36	1.67	
Average roller speed (m /hr)	3000	3250	4022	
Compacted lift thickness (m)	0.5	0.5	0.5	
No. of roller passes required	8	8	8	
Efficiency	0.75	0.78	0.8	
Productivity (cum / hr)	323.44	373.91	337.04	1034.39

Number of generations or iterations are 67 and population size is 50. Mutation and crossover rate are 0.1 and 0.5 respectively.

Final result after completing the GA optimization process

Table 12: Test results of productivity optimization of steel drum vibratory roller after analysis in EVOLVER 5.7

Factor description	Models			
	L&T 1107D	IR –SD 110	DYNAPAC CA 150D	Total productivity (cum. / hr.)
Maximum operating weight (tones)	11.3	10.8	9.3	
Compacted width per roller pass (m)	2.3	2.36	1.68	
Average roller speed (m /hr)	4825.22	4276.96	6000	
Compacted lift thickness (m)	0.5	0.5	0.5	
No. of roller passes required	9.63	9.89	11.82	
Efficiency	0.81	0.76	0.8	
Productivity (cum / hr)	468.93	387.73	340.04	1196.70

Table 13: Comparative analysis of owning and operating costs for vibratory steel drum rollers (Case 1 and 2)

Model	Total cost (Rs./hr.)
L&T 1107 D	828
IR-SD 110	940
DYNAPAC CA 150D	770

CONCLUSION

Considering all the four models of hydraulic excavators of Case 1 and 2 it is observed that the difference between actual productivity on site and the productivity as computed through equation (1) is about 7.9 % and the difference between the computed productivity and the optimized productivity is about 7.8 % (refer table 8).

Genetic algorithm- an optimization tool was used to optimize productivity having cross over and mutation rate of 0.5 and 0.1 respectively. The population size is 50 and number of iterations are 63. There were four constraints, which were solved by the constraint solver. As obtained through the analysis by EVOLVER 5.7 software, the productivity value (as computed through equation 1) for L&T Komatsu PC 300-7 and Volvo EC 210 BLC remain same after optimization using genetic algorithm (refer table 8). For both models, after 63 iterations the values changed depending on the constraints and adjustable cells but at the end of the all iterations genetic algorithm has given the same values of optimum productivity as that of computed values. In other two models like JCB 3DX and TATA Hitachi EX 110, the value of productivity has changed due to change in fill factor and efficiency factor respectively. It appears that in TATA Hitachi EX 110 model, the efficiency can be increased up to 0.89 (refer table 7) from 0.7 (refer table 5) and in JCB 3DX the optimum productivity is obtained at an increased fill factor of 1.15 (refer table 7) against the pre optimization fill factor value of 1.05 (refer table 5). Productivity of the vibratory steel drum rollers as computed by incorporating the values of the factors in the productivity equation (2), for L&T 1107D, IR-SD 110 and DYNAPAC CA 150D are 323.44, 373.91 and 337.04 cum / hr respectively. After carrying out 67 iterations for population size of 50 and for mutation and crossover rate are 0.1 and 0.5 respectively the optimized productivity as given by EVOLVER 5.7 software are 468.93, 387.73 and 340.04 cum. / hr respectively. Thus the total optimized productivity as given by EVOLVER 5.7 software for three different vibratory steel drum rollers is about 1196.70 cum. / hr, which is about 15.69 % higher than the computed productivity (1034.39 cum. / hr). Also, since the increase in optimized productivity is maximum for L&T 1107D, which is about 44.98 % and the owning and operation cost is also quite reasonable and is Rs.828 / hr (refer table 13), thus this L&T 1107 D appears to be more feasible and should be selected for carrying out more work by the project authorities. Further as the concept is generic, this tool can be applied for selection and optimization of other equipments used in highways and other infrastructure sector.

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This is a pure academic research with no intention to promote or discourage any brand of construction equipments.

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