Analysis of Earth-Moving Systems Using Discrete-Event Simulation

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Abstract: This paper outlines experiments performed on a simulation model of excavator-dump-truck-type earth-moving operations with the intention of indicating the parts of an earth-moving system to which the output is most sensitive. Response-surface methodology was used initially to indicate the relationship between two factors: the truck travel time, from loader to dump area and back; and the truck spot (or maneuver) time at the loader. This method indicated that the form of the relationship between these factors varied at different values but did not indicate how often factors affected the output. Full factorial designs were then done that not only were more economical in terms of the number of experimental runs required but also indicated that the most important factors are number of trucks, the haul and return (travel) time, the number of passes per load, and the loading rate. The simulation has highlighted a number of sensitivities. If load pass time is reduced then production will not increase if the operation is already under resourced. Conversely, production will not automatically increase by adding more trucks to the operation.

INTRODUCTION

Wheeled tractor-scrapers are normally the first choice for short-haul earth-moving operations. However, increases in U.K. fuel costs, together with a slowing down of the construction of the U.K. motorway network, have resulted in a regional decline of the motor scraper as a cost-effective method of earth moving. U.K. contractors have therefore turned to the backhoe excavator and a fleet of rigid or articulated dump trucks as a practical and cost-effective alternative. Similar scenarios can be seen in continental Europe, where high fuel costs also exist, as opposed to North America and the Middle East, where fuel costs are relatively low. It is against this high-fuel-cost scenario that this work has been undertaken.

In today's increasingly competitive market, the contractor needs to be able to plan and estimate an earth-moving contract as accurately as possible at tender stage and, if the contract is won, control site operations to keep costs to an absolute minimum. However, production estimates at a tender stage are difficult to calculate accurately and at a construction stage, production targets are hard to maintain. This is because an earth-moving system is extremely complex. If we consider the earth-moving system defined mathematically:

$$Y = f(k_1, k_2, k_3, \ldots k_n) \tag{1}$$

where Y = a response of the system to certain values of k_1, k_2, k_3, . . . k_n, which are called *factors*; and f = response surface. If it were to be investigated how a response—say, earth-moving production rate, in cubic meters per hour—varied for certain factor values—e.g., truck volume, truck speed, or load time—one method would be to physically experiment with the system in the field: change the factor values and note the change in the response. Practically, this is very difficult for a number of reasons, most important of which is that a large number of experimental runs would be required to give a good indication of which way the response changes. If each run has to consist of at least 5 h of physical operation time, then for more than a few runs this approach would have to be abandoned due to cost and time constraints.

What is required, therefore, is a mathematical model on which a type of quasi-experiment can be performed. The system is too complex to be analyzed deterministically. Therefore, a simulation model and computer program have been developed on which experiments can be designed and performed. This paper outlines experiments performed using response-surface methodology (Myers et al. 1989) and factorial analysis (Box et al. 1978).

EARTH-MOVING SYSTEM: FACTORS AND RESPONSES

Fig. 1 shows a schematic of the earth-moving system, which is a variation of the classic queueing system—for example, a bank or a car wash. Trucks are used in this system to transport material from the cut area to the fill area, and these are (in queueing-theory terminology) the customers. The servers are the excavator loaders, which fill the trucks one at a time by drawing them from the queue. The service time is therefore built up from individual component times that are the maneuver or spot time, which is the time the truck takes to get from the queue to its position by the loader, and the load time, which is made up of individual load pass times. The trucks, once loaded, haul to the dump area, dump the load and return to the queue. The length of time of this "back-cycle" (or time out of service) is heavily dependent on the speed of the trucks and the length of the haul and so, to allow

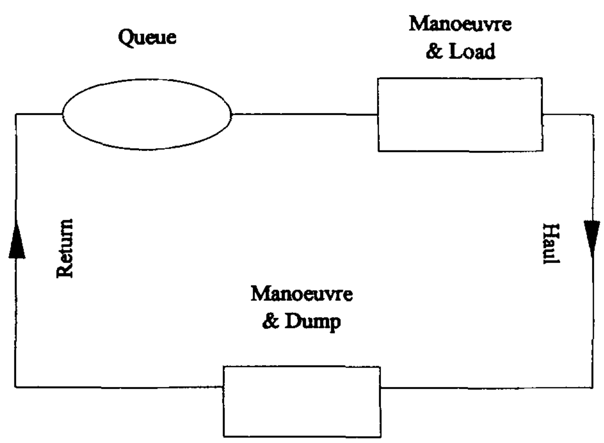

FIG. 1. Earth-Moving System

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TABLE 1. Factors and Responses for the Earth-Moving System

First-order factors (1)	Second-order factors (2)	Responses (3)
	(a) Travel System	
Haul-road soil parameters	—	Production (m^3/h)
Haul-road gradient	—	Truck use (%)
Haul-road length	—	Excavator use (%)
Truck weight	Travel time (mean)	Queue wait time (s)
Vehicle specification (engine size, transmission type, drive system, suspension system)	Travel time (variability)	Match factor
Number and type of obstructions (type of plant crossings, size of bailey bridges)	—	Cost per cubic meter (to excavate, load, and haul)
Driver ability	—	—
	(b) Spot System	
Load area size	Spot time (mean)	—
Size and type of trucks	Spot time (variability)	—
Driver ability		
	(c) Load System	
Cut depth		
Soil parameters	Load pass time (mean)	—
Type of excavator	Load pass time (variability)	—
Operator ability		
	(d) Dump System	
Dump-area size	Dump time (mean)	—
Driver ability	Dump time (variability)	—
	(e) Other Factors	
—	Number of trucks	—
—	Bucket volume	—
—	Bucket passes per load	—

for both factors, the haul and return times have been collectively classified as travel time. The final time component is the dump time, which tends to have the same distribution for all types of dump trucks. There is more than one response to this system other than production—for example, plant use, queue wait time, and length and match factor. (See Appendix I for a definition of match factor.) Affecting these responses, the system has many factors on various levels. For example, truck travel time is a factor, but this itself can be considered as a response to a subsystem with factors such as engine specification, haul road soil properties, haul road length and gradient. Table 1 outlines the subsystems, some of the first- and second-order factors, and the responses that could be considered in an investigation of the earth-moving system.

As can be seen, the earth-moving system can be split into four separate subsystems, each with its own factors leading to two responses: a mean and a variability for each time component. These become eight factors for the main system along with three additional factors leading to six responses. It is these final responses that the estimator and engineer are interested in to minimize time, cost, and resources to complete the job. To consider all the factors, first- and second-order, in one simulation model would be an extremely complex procedure; indeed, some factors are difficult to quantify (driver ability, for example). The simulation model that has been developed, therefore, only considers the second-order factors. Time-component means and variabilities are determined prior to simulation runs using a database of observed times from various sites in the United Kingdom. One exception is the travel time. This can be calculated manually on a separate simulation package such as Accelerator (*Accelerator* 1987) or Vehsim (*Vehsim* 1987).

SIMULATION MODEL AND PROGRAM

The simulation model developed is based on a discrete-event simulation method used extensively in the manufacturing and production engineering industries (Law and Kelton 1991; Law 1986; Law and McComas 1989). Discrete-event simulation is used where the state of the system changes at discrete, measurable points in time; in the earth-moving system, these events are when a truck arrives at the queue and when it departs upon completion of loading. The occurrence of these events can be recreated on a computer by generating random times from the expected probability density functions for a particular operation. The simulation model was transferred to a computer by way of a program written in C to perform simulation runs. The inputs to the program are the 11 second-order factors shown in Table 1. To keep the initial model as simple as possible, number of trucks, bucket volume, and number of bucket passes per truck load are entered as individual integers, although these factors will have their own distributions for a real-life operation. If necessary, the model can be altered if more accuracy is required. The mean and variability for the four time components are entered as parameters for the Erlang distribution (Carmichael 1986; 1987a, b), which is a form of the gamma distribution with integer shape factors.

The simulation program is run until the internal simulation clock has reached the equivalent of a prespecified real-time limit, usually a single earth-moving shift between breaks, i.e., 3 h. At this point the simulation is stopped and the report generator invoked (Fig. 2). The report generator gives five of the six responses shown in Table 1; the sixth, the cost per cubic meter, can be calculated from a knowledge of the plant costs per hour. Replications for the same run can be done automatically: The seed for the random number generator is changed for each replication and the results can be stored in a text file that can be viewed in any spreadsheet. It is with this program that experiments have been done. For the experiments detailed in this paper, approximately 2,100 individual replications have been run.

```
                S I M U L A T I O N   R E S U L T S


                  Reference Code:   Example.a
                            Seed:   20
                  Total Run Time:   10821    secs.
            No. Cycles Completed:   73

                     No. Haulers:   4
                 Passes per Load:   8
                 Volume per pass:   1.95 Bank Cu.m
                    Match Factor:   0.94
   Productivity after Mismatch:     257  m3/hr

         Dump-Truck Utilisation:    81   percent
             Loader Utilisation:    93   percent

              Average Spot Time:    28   secs.
              Average Load Time:    143  secs.
              Average Dump Time:    87   secs.
            Average Travel Time:    332  secs.
            Average Truck Delay:    29   secs.
           Average Loader Delay:    24   secs.
       Average Truck Cycle Time:    621  secs.

           Overall Productivity:    221  m3/hr

Press c to Continue_
```

FIG. 2. Typical Results Report from Simulation Program

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RESPONSE-SURFACE DESIGNS

Of the 11 factors of the simulation model of the earth-moving system, suppose 10 were kept at a constant level and the 11th was varied over a particular range of interest. If the response is plotted against the varying factor, the resulting curve is a response curve. For example, Table 2 shows the values of 10 factors, and Fig. 3 shows the production response curve obtained from simulation runs as the travel time is varied from 100 to 1,200 s. Such a change in travel time may be due to a change in haul length or a change in speed due to differing ground conditions. This curve is limited in that it shows how the response varies for a very small portion of the overall function for the response. There is no doubt that it is valid for the configuration in question, but it gives no indication as to how the response will behave for all other values for all other factors.

If two factors were varied, with the other nine factors kept constant, a response surface (i.e., a three-dimensional representation of the factors in question for the particular range of interest) is obtained. For three or more factors, a response surface cannot be graphically represented and the experimenter will have to be satisfied with sectional representations of the entire surface.

Fig. 4 shows a response surface obtained when spot times and travel times are varied. Changes in spot time could be due to changes in load area size and shape and changes in travel time will occur due to a lengthening of the haul road and/or changes in ground conditions. Mean spot time was varied from 10 to 22 s, mean travel time varied from 100 to 1,100 s, and all other factors were kept at the same level as shown in Table 2. The curve in Fig. 3 is therefore one single section through the surface shown in Fig. 4. From a brief inspection of Fig. 4, the simple conclusion that spot time has little effect on the production response could be drawn: At travel time of 100 s, the response changes only 10%, while at travel time of 1,100 s, the change in response is virtually nothing (0.7%). However, in this example, the travel times are set at much higher levels than the spot times and the increase in travel time is 1,000% compared with only a 100% increase in spot time. This indicates that the response surface is little better than a response curve for this particular system; conclusions about how the levels of the factors outside the particular range studied will affect the response cannot be drawn.

In Fig. 5, travel time and spot time are varied again but travel time is varied from 50 s to 200 s. It can be seen how spot time has a greater influence on the production response than in Fig. 4. However, what is unknown is how the levels at which the other factors have been set have affected the response and whether any interactions are present. For example, there may be an interaction between load pass time and travel time that influences the response. It is impossible to determine from these response surface designs whether such interaction exist and, if they do, whether they caused the difference in productions between Figs. 4 and 5.

TABLE 2. Factor Levels for Response Curve

Factor (1)	Level (2)
Travel-time variability	k = 40
Spot-time mean	10 s
Spot-time variability	k = 10
Load-pass time mean	16 s
Load-pass time variability	k = 10
Dump-time mean	90 s
Dump-time variability	k = 20
Passes per load	6
Bucket volume	2 bank m^3
Number of trucks	5

FACTORIAL DESIGN

So far, this paper has shown that the earth-moving system has at least 11 factors, all of which will have some effect on at least six responses. First attempts at response-surface design have shown perhaps the most fundamental problem facing all experimentalists: which factors are the most important and over which ranges shall they be studied. Box et al. (1978) indicated a paradoxical situation: The best time to design an experiment is when it has been completed. Experimentation is therefore iterative; after each successive experiment, more will be known about the system and future experiments will be more useful. Factorial designs are useful in this respect in that they can give a "broad picture" of the overall system

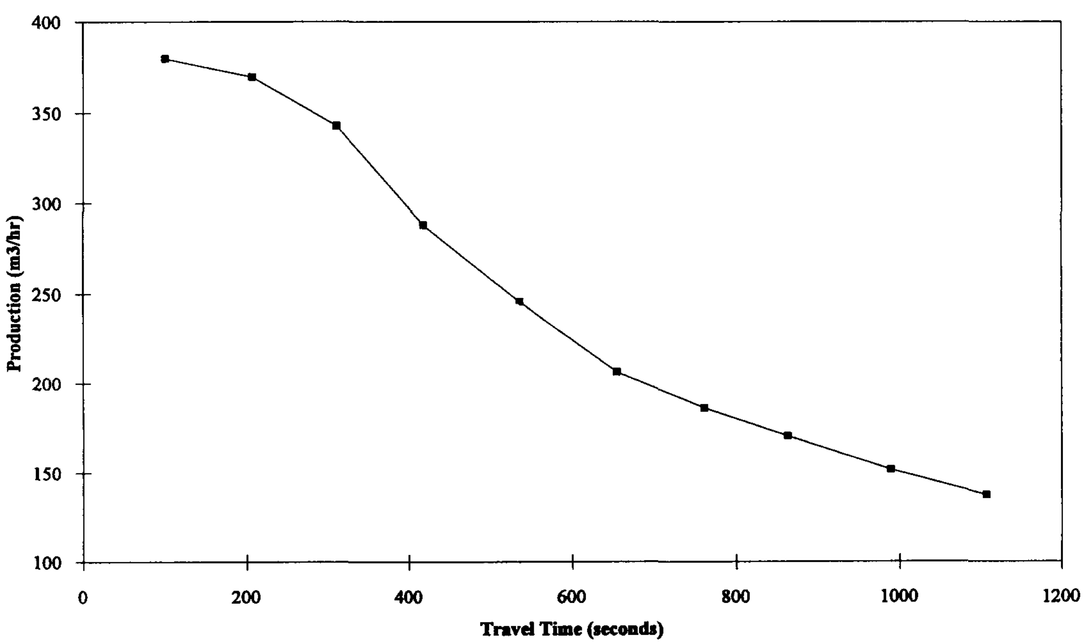

FIG. 3. Response Curve for Factor Levels in Table 2

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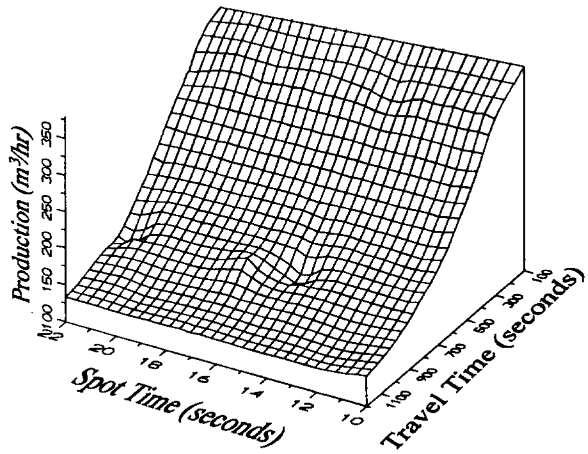

FIG. 4. Response Surface for Spot Time and Travel Time

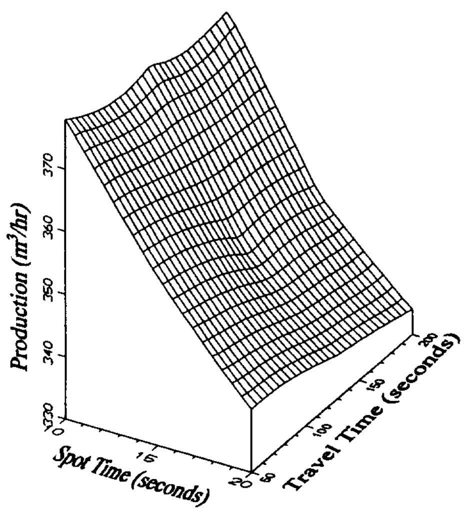

FIG. 5. Response Surface for Spot Time and Travel Time (Reduced Travel Time)

and will help eliminate factors that have little effect on responses.

In performing a factorial design, a set number of values or levels for each factor are chosen, and experimental runs for all combinations of levels are performed. For example, if a system with only three factors was to be experimented with and three levels were chosen for each factor, then $3^3 = 27$ experimental runs (or design points) would be required. Unfortunately, if three levels for each of the 11 factors in this simulation model were chosen, then $3^{11} = 177{,}147$ runs would have to be performed; this is clearly impractical. The simplest is two levels for each factor, but even this requires 2,048 runs, which is also too many for an initial investigation.

A different approach was therefore taken with the earthmoving system. On the basis of the work of Carmichael (1987a, b), the effective number of factors was reduced by grouping four factors after making the assumption that pairs of factors (i.e., load and spot, and dump and travel) have the same effect on the output. Referring to Fig. 1, the spot and load-cycle times are collectively known as the service time; the travel and dump times are collectively the back-cycle times. In effect, the four time factors are reduced to two—service and back-cycle—and these have been represented by load pass time and travel time.

A simplifying assumption has also been made by eliminating the bucket volume from any designs. In a real-life situation, the bucket volume will effect the production in two ways: the load-cycle duration (larger buckets will lead to fewer, slower passes) and volume per pass (larger volume per cycle from a larger bucket with the same number of passes). However, the model does not include any relationship between bucket size and load pass time; the model output will therefore be linearly proportional to the bucket size. Although this may not represent a real-life situation completely accurately, initial models must be kept simple and therefore bucket volume shall be kept at a single level in these experimental situations.

At this stage, the effective number of factors is now six, and a 2^6 factorial design requires 64 design points. This is a far more practical figure for an initial experiment.

2^6 FACTORIAL DESIGN: INITIAL STUDY

Table 3 shows the 2^6 experiment for the six remaining factors. The two levels for each factor are coded by a positive and a negative, and in this case the negative is associated with the lower numerical value. Runs were done at each of the 64 design points, with 11 replications for each point. Production and match factor responses were recorded for each replication and the average of the 11 replications for each design point are shown, along with the design matrix for the experiment in Table 4.

The main effect of a factor is the average change in a response due to moving a factor from its minus level to its plus level, while all other factors are fixed. The average is taken for all combinations of the factors in the design. The main effect on production of factor 1 (number of trucks) is therefore:

$$e_1 = \frac{(P_2 - P_1) + (P_4 - P_3) + \cdots + (P_{64} - P_{63})}{32} \quad (2a)$$

for effect 1 in this example:

$$e_1 = \frac{-P_1 + P_2 - P_3 + P_4 \cdots - P_{63} + P_{64}}{32}$$

$$= \frac{-179.6 + 373.1 - 153.2 + 226.1 \cdots - 39.2 + 103.0}{32}$$

$$= 82 \quad (2b)$$

Comparison of (2*a*)–(2*b*) and Table 4 shows that the effects can be computed by applying the relevant sign for the factor to the response at each design point, summing them, and dividing by 2^{r-1}, which in this case is 32. All main effects on both production and match factor for each factor are perhaps best calculated using a spreadsheet; lengthy hand calculations would be prone to error.

As well as calculating the main effects for each factor, interaction effects between factors can also be determined in a similar way. [For full deviation of interaction effects see Box et al. (1978) or Law and Kelton (1991)]. For example e_{25}, the interaction between factors 2 (passes per load) and 5 (travel-time mean) is calculated by first adding another column to the design matrix headed 2 × 5. The signs for each

TABLE 3. Factor Levels for Six-Factor Experiment

Factor (1)	Factor number (2)	Negative level (3)	Positive level (4)
Number of trucks	1	2	6
Passes per load	2	4	7
Load pass time (mean)	3	12	22
Load pass time (variability)	4	$k = 20$	$k = 10$
Travel time (mean)	5	100	800
Travel time (variability)	6	$k = 70$	$k = 50$

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TABLE 4. Design Matrix for Six-Factor Experiment

Design point (1)	Factor Number 1 (2)	2 (3)	3 (4)	4 (5)	5 (6)	6 (7)	Production (8)	Match factor (9)
1	−	−	−	−	−	−	179.6	0.49
2	+	−	−	−	−	−	373.1	1.50
3	−	+	−	−	−	−	153.2	0.70
4	+	+	−	−	−	−	226.1	2.18
5	−	−	+	−	−	−	156.9	0.67
6	+	−	+	−	−	−	242.0	2.08
7	−	+	+	−	−	−	122.7	0.95
8	+	+	+	−	−	−	135.7	3.16
9	−	−	−	+	−	−	179.8	0.49
10	+	−	−	+	−	−	375.9	1.49
11	−	+	−	+	−	−	153.6	0.78
12	+	+	−	+	−	−	220.0	2.22
13	−	−	+	+	−	−	155.4	0.69
14	+	−	+	+	−	−	233.5	2.14
15	−	+	+	+	−	−	119.6	0.98
16	+	+	+	+	−	−	130.9	3.18
17	−	−	−	−	+	−	44.2	0.13
18	+	−	−	−	+	−	124.2	0.40
19	−	+	−	−	+	−	42.0	0.21
20	+	+	−	−	+	−	116.3	0.64
21	−	−	+	−	+	−	42.1	0.20
22	+	−	+	−	+	−	119.1	0.60
23	−	+	+	−	+	−	39.6	0.33
24	+	+	+	−	+	−	107.0	0.99
25	−	−	−	+	+	−	44.0	0.13
26	+	−	−	+	+	−	123.3	0.41
27	−	+	−	+	+	−	42.4	0.22
28	+	+	−	+	+	−	117.3	0.66
29	−	−	+	+	+	−	42.6	0.20
30	+	−	+	+	+	−	119.5	0.62
31	−	+	+	+	+	−	39.7	0.34
32	+	+	+	+	+	−	105.3	1.05
33	−	−	−	−	−	+	176.3	0.49
34	+	−	−	−	−	+	372.4	1.47
35	−	+	−	−	−	+	150.8	0.70
36	+	+	−	−	−	+	225.7	2.16
37	−	−	+	−	−	+	154.2	0.66
38	+	−	+	−	−	+	242.3	2.04
39	−	+	+	−	−	+	120.9	0.95
40	+	+	+	−	−	+	135.5	3.08
41	−	−	−	+	−	+	173.1	0.49
42	+	−	−	+	−	+	361.1	1.50
43	−	+	−	+	−	+	148.6	0.71
44	+	+	−	+	−	+	218.5	2.19
45	−	−	+	+	−	+	152.2	0.67
46	+	−	+	+	−	+	233.6	2.09
47	−	+	+	+	−	+	118.6	0.96
48	+	+	+	+	−	+	131.6	3.07
49	−	−	−	−	+	+	43.5	0.13
50	+	−	−	−	+	+	122.8	0.41
51	−	+	−	−	+	+	42.5	0.21
52	+	+	−	−	+	+	115.6	0.64
53	−	−	+	−	+	+	42.8	0.20
54	+	−	+	−	+	+	116.9	0.60
55	−	+	+	−	+	+	39.5	0.33
56	+	+	+	−	+	+	104.2	1.01
57	−	−	−	+	+	+	43.6	0.13
58	+	−	−	+	+	+	121.6	0.41
59	−	+	−	+	+	+	41.0	0.21
60	+	+	−	+	+	+	114.7	0.65
61	−	−	+	+	+	+	42.9	0.21
62	+	−	+	+	+	+	117.2	0.63
63	−	+	+	+	+	+	39.2	0.34
64	+	+	+	+	+	+	103.0	1.04

design point in this column are simply the product of the signs in the factor 2 column and factor 5 column. This two-factor interaction is calculated in the same way as for main effects: summing the dot products of the 2 × 5 column and the response column and dividing again by 2^{r-1}. (Two-factor interactions are symmetrical; i.e., $e_{25} = e_{52}$.) Three- and higher-factor interactions are calculated in exactly the same way.

Fig. 6 shows the main effects as well as two-factor and three-factor interactions calculated for this initial study. Four- and higher-factor interactions were negligible. It is difficult to say whether some of the smaller effects are real or are just the result of random fluctuations or noise. To determine the significance of an effect we must estimate its variance. There are several methods to achieve this; Law and Kelton (1991) suggest replicating the design n times and obtaining n independent values for each effect. Confidence intervals can thus be obtained using the t distribution. In this case, with 11 separate replications for each design point (i.e., a total of 704 replications) such a method is a daunting task and therefore the method proposed by Box et al. (1978) has been used. This method is based on the assumption that the variations between replications for each set of conditions can be used to estimate the standard deviation of a single response and thus the standard deviation of the effects. The assumption requires the variation between runs at one set of experimental conditions to be a reflection of the total variability affecting runs at other conditions; in this case the assumptions will hold as each replication is done with a different set of random numbers.

If g design points are replicated with n_i replications made at the ith point, giving an estimate s_i^2 of the variance σ^2 with $\nu_i = n_i - 1$ degrees of freedom then the overall estimate of run variance is given by

$$s^2 = \frac{\nu_1 s_1^2 + \nu_2 s_2^2 + \cdots + \nu_g s_g^2}{\nu_1 + \nu_2 + \cdots + \nu_g} \tag{3}$$

Here, $g = 64$ and $n_i = 11$, $\nu_i = 10$ for each design point. Therefore (3) reduces to

$$s^2 = \frac{\sum_{i=1}^{g} s_i^2}{g} \tag{4}$$

which gives $s^2 = 0.082$ for match factor and $s^2 = 5.248$ for production. Each main effect and interaction is the difference between the averages of the responses when the factors are at the plus level and the averages of the responses at the minus level. Each average contains a total of 352 responses [i.e., (64/2) × 11)], which gives the variance of each effect to be:

$$V(\text{effect}) = \left(\frac{1}{352} + \frac{1}{352}\right) s^2 \tag{5}$$

giving V(match factor effects) = 4.65×10^{-4} and V(production effects) = 0.030. The estimate for standard error for each response is $\sqrt{V}$ giving se(match factor effects) = 0.022 and se(production effects) = 0.173. These errors are quite small, almost negligible, and are a reflection of the high number of replications carried out for each design point. We can conclude, therefore, that the effects and interactions shown in Fig. 6 with values greater than these standard errors are statistically significant.

This initial factorial design has indicated that:

- The change in variability of the component times (spot and load pass time) have very little effect on both the production and the match factor compared with the other factors. Furthermore, these factors do not significantly interact with any other factors. It is safe, therefore, to keep these factors at a constant level in future experiments.
- There are a number of two-factor interactions and two significant three-factor interactions. The effects of factors

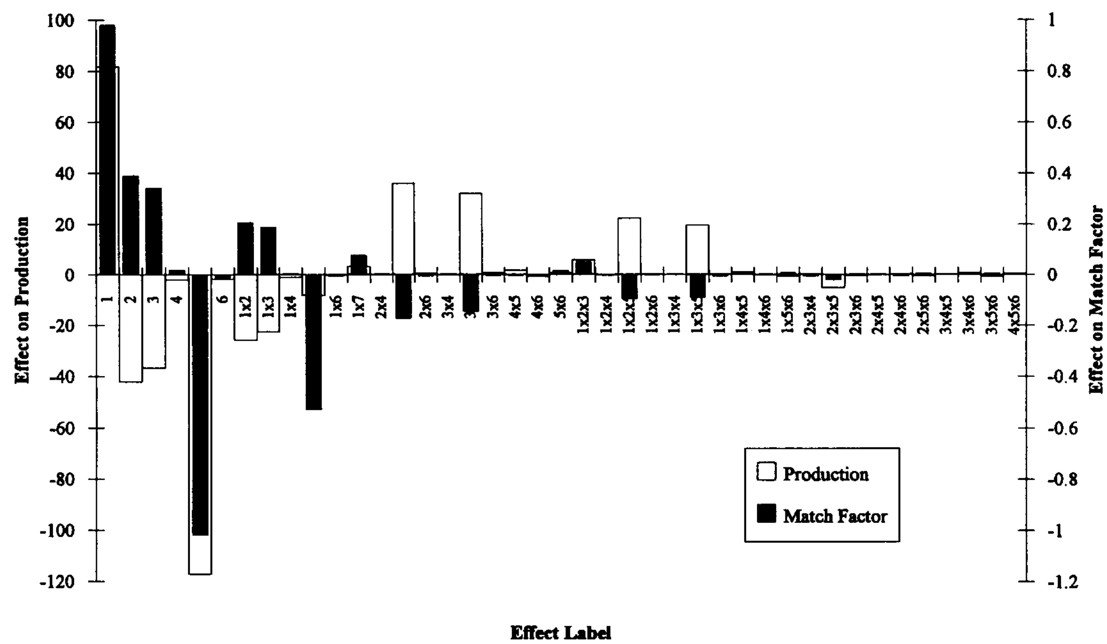

FIG. 6. Main Effects and Two- and Three-Factor Interactions for Six-Factor Experiment (For Factors, See Table 5)

1, 2, 3, and 5 cannot be interpreted separately because of these interactions. In particular, the model correctly predicts the intuitive answer: that the match factor is very sensitive to the levels at which the number of trucks and the travel time mean are set.

- This initial experiment was a sensitivity analysis and has shown which effects and interactions are significant as well as where further study should be undertaken. These studies should be done at levels of the factors that are more appropriate to a real situation. For example, in a single, real earth-moving operation, a change of travel time from 100 to 800 s was unlikely, but this has indicated the significance of the factor's influence on the output.

Now that the earth-moving situation has been trimmed down to the most significant factors, the final experiment in this paper will be a factorial design based on an actual site operation. This should yield more realistic results that indicate the sensitivity of the earth-moving output to the factor levels.

2^4 FACTORIAL DESIGN: CASE STUDY

The exercise that this design is based on was an actual earth-moving operation for the construction of a dual three-lane motorway in the United Kingdom. This motorway was built in a deep cutting in the chalk that is predominant in southern United Kingdom. The excavator used was a Caterpillar 245B backhoe moving an average of 1.80 m^3 of chalk every pass. This figure was obtained from an actual measurement of the earth moved in a single shift (using surveying equipment) and a count of the number of buckets of material loaded. The total volume moved divided by the number of buckets gave

TABLE 5. Factors for Four-Factor Experiment

Factor (1)	Factor number (2)	Negative level (3)	Positive level (4)
Number of trucks	1	7	6
Passes per load	2	6	7
Load-pass time mean	3	17	14
Travel-time mean	4	492	405

TABLE 6. Design Matrix for Four-Factor Experiment (Values Coded)

Design point (1)	Factor Number 1 (2)	2 (3)	3 (4)	4 (5)	Production (m^3/h) (6)	Match factor (7)	Cost (units/m^3) (8)
1	−	−	−	−	127.7	1.30	468
2	+	−	−	−	118.8	1.10	445
3	−	+	−	−	132.4	1.47	452
4	+	+	−	−	129.8	1.23	408
5	−	−	+	−	140.8	1.12	425
6	+	−	+	−	125.1	0.95	423
7	−	+	+	−	154.0	1.24	388
8	+	+	+	−	140.7	1.06	376
9	−	−	−	+	134.8	1.43	444
10	+	−	−	+	132.4	1.22	400
11	−	+	−	+	136.1	1.63	439
12	+	+	−	+	136.2	1.37	388
13	−	−	+	+	152.7	1.27	392
14	+	−	+	+	140.5	1.09	377
15	−	+	+	+	157.4	1.43	380
16	+	+	+	+	154.2	1.21	343

an average bucket size in bank cubic meters, thus allowing for bulking. The dump trucks were Volvo BM A35 articulated dump trucks carrying an average of six passes, i.e., 10.8 bank m^3 of earth per load. Average spot time was 29 s; average dump time was 87 s. The remaining four factors were recorded and used as the negative level in a 2^4 factorial design. Table 5 shows the positive and negative levels used. The values used at the positive level were chosen to represent what would be an anticipated improvement in the overall efficiency of the operation. First, the number of trucks was reduced by one at the positive level as the operation was initially overresourced (indicated by an initial match factor of 1.23). A reduction by one truck should bring the match factor closer to one and thus give greater efficiency. The number of passes per load was increased by one at the plus level, the dump trucks used were able to carry the extra load (which is only 1.8 m^3, or approximately 3.2 t). The load pass and travel times were both reduced by 17.5% to give the plus level. The design matrix is shown in Table 6.

The design was replicated 11 times at each design point, and responses were recorded for the match factor, production, and cost per cubic meter (which is perhaps the most

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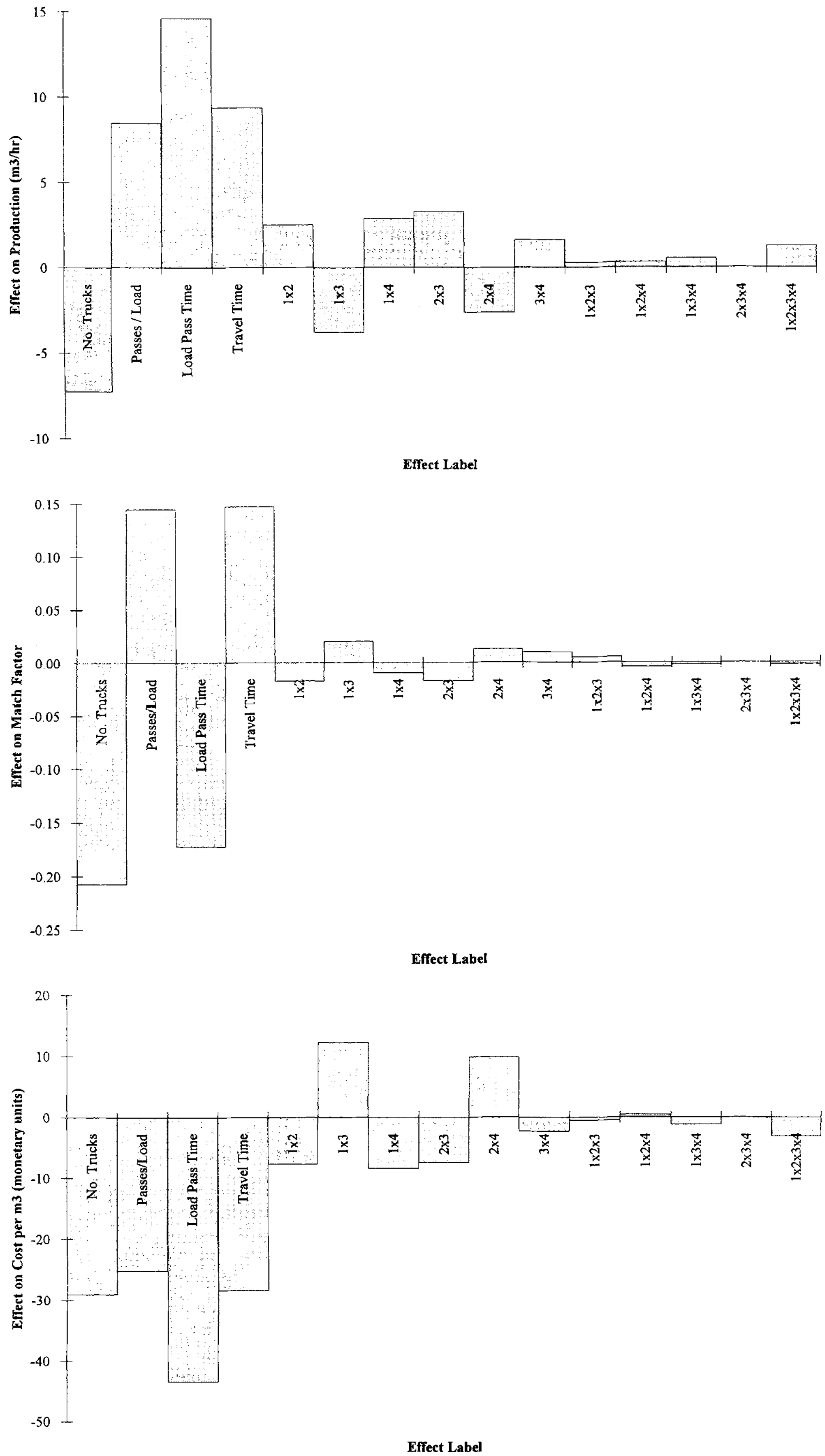

FIG. 7. (a) Main Effects and Two-, Three-, and Four-Factor Interactions on Production for Four-Factor Design (Production Values Coded); (b) Main Effects and Two-, Three-, and Four-Factor Interactions on Match Factor for Four-Factor Design; (c) Main Effects and Two-, Three-, and Four-Factor Interactions on Cost per Cubic Meter (Cost in Arbitrary Monetary Units)

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interesting response for an earth-moving contractor). The average values of the responses are shown in Table 6. Figs. 7(a)–7(c) show the main effects and interactions for the responses. (Note, however, that actual values of production and cost have been coded for reasons of confidentiality.) The overall standard error was also calculated, as for the initial study, and again, due to the high number of replications, these errors are very low. [*se*(match factor effects) = 0.0038; *se*(production effects) = 0.603.] Several observations can be made from these results:

- The factor with the greatest effect is the loader pass time. In this example, a reduction from 17 s per pass to 14 s will, on average, decrease the cost per cubic meter by approximately 9% and increase the production by 11%. These times are actually faster than those quoted in the *Caterpillar Performance Handbook* (1993), but in this situation the dry brittle chalk is extremely conducive to quick loading.
- Of the interactions, three- and four-factor interactions are virtually negligible but the two-factor interactions are significant. Surprisingly, although most factors have an improving effect on the responses, two interactions (number of trucks/load pass time and passes per load/travel time) have a negative effect that may seem at first to be difficult to explain. The reason can be seen from Fig. 7(b)—match factor effects. Factors 1 and 3 tend to reduce the match factor, while factors 2 and 4 will increase the match factor. Appendix I shows that the most efficient operation will occur at a match factor of 1, so combining the effects of factors 1 and 3, for example, will push the match factor to well below one and thus reduce efficiency. Factors 2 and 4 combined will force the match factor even higher than the initial value, again reducing efficiency.
- The effect of reducing the number of trucks by one did not bring about the anticipated increase in production. On its own, reducing the number of trucks would reduce the match factor to approximately one. However, the changes in the other factors also brought the match factor down to a more efficient level and a reduced fleet size pushed the match factor even lower—with subsequent reduction in queue length and loader use. In conclusion, the number of trucks should have been kept at seven although another experiment would have to be done to find out the exact effect. (If this factor were to be kept constant, a factorial design would effectively be with three factors giving 2^3 or eight design points.)

IMPLICATIONS FOR EARTH-MOVING PRACTICE

This paper attempts to determine which factors, and what levels of these factors, affect the output responses of an earth-moving model the most. The output of the model is sensitive to six factors: number of trucks, passes per load, load pass time, spot time, travel time, and dump time. Four of these factors can be split into two groups of two: The effect on the response of dump time is the same as that for travel time; and spot time has the same effect as load pass time.

- Number of trucks. This factor is perhaps the one that is easiest to control by the contractor. The previous experiment showed that the correct number of trucks is essential for maximum efficiency. Experienced contractors will be able to instinctively assess a live operation and adjust the number of trucks. However, for operations yet to be done and for long-haul operations with many trucks, this is not as easy; the impact on the output response to changes in fleet numbers should be understood.
- Passes per load. Like the number of trucks, this is easily controlled, and despite an increase in load time, an extra bucketful per load is advantageous. The value of an extra bucket, however, will depend on a number of factors. First, the time out of service (back-cycle time) is important. If the ratio of back-cycle time to service time is large, then any increases in the service time due to an extra bucket will be less significant than if the back-cycle time is short. Therefore, for short hauls, an extra bucket may not improve the production and may, in fact, prove to be detrimental (see comments on spot and load pass times later). Second, the state of the truck queue will influence the value of an extra bucket: If there are trucks waiting, then it may be better to have fewer passes and increase truck use. Indeed, observations made on real sites have shown that if an operation is overresourced, loader operators will tend to underload a truck to reduce the queue length. Third and perhaps most important, an extra bucket should never cause the truck payload to exceed its limit. Apart from long-term damage to the trucks and the fact that some materials, especially wet clays, will take longer to dump if the truck is overloaded, safety considerations should be paramount. The danger of material falling from overloaded trucks is ever-present, especially on narrow construction sites and where live traffic is present.
- Spot and load pass time. These factors both have the same effect on the output. For the operation studied with the 2^4 design, load pass time had the greatest effect on cost and production, and this will generally hold true for operations with short hauls. (On longer hauls, the travel time will become the dominant factor.) Therefore, the contractor should try to reduce spot and load times. Spot time can be controlled by having a large, clear maneuvering area and will reduce with good truck discipline, i.e., queuing as close to the loader as possible and moving into place as soon as the previous truck has departed. For operations with large numbers of trucks, it is worth having a foreman in charge of "directing" the plant into place. Load time is governed by a number of factors, some more controllable than others. For example, the contractor has little control over the type of material but the excavating operation should be set up to minimize swing angle and optimize the cutting depth. This depth is dependent on the machine size, excavator arm length, and height of the dump truck, so each dump-truck/excavation combination will have different optimum operating conditions.
- Travel and dump times. Especially on long hauls, the travel time is a major factor in the earth-moving system and is influenced by many factors. Unless the haul road is purpose-built, the plant will have to run over the actual cuttings and embankments that make up the works, and little can be done to change the soil properties. However, careful maintenance of haul roads and an awareness of how rain will affect the strength of the soil is needed to maximize the running speed. Other factors influencing the travel time are obstructions, such as bailey bridges and plant crossings, haul road gradient, and truck specification.

The presence of interactions between the factors, which can only be detected by certain experimental designs, have indicated the following:

- Care should be taken when trying to improve an operation that changes made do not have a detrimental effect on the output. Fig. 6 has shown that certain combinations of level changes will, at best, leave the output unchanged.

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load pass time, essentially, there is no point in reducing load time if there are not enough trucks to satisfy the loader.

- Interactions between effects mean that the response cannot be expressed as a linear function. First, this reinforces the assumption that simulation is a valid way to study the earthmoving system as simulation requires no mathematical relationship between the input and output. Second, it means that the effects of the factors cannot be interpreted outside the range that they have been given for the experiment. The experiments outlined in this paper have therefore been useful in indicating the important factors for the ranges presented, but many more studies would be needed to investigate how they affect the responses for all possible values that could be encountered in a live situation.

The largest interaction is between number of trucks and

CONCLUSIONS

The sensitivity of the operational output on the following factors has been shown: number of trucks, passes per load, load pass time, spot time, travel time, and dump time. It is less sensitive to factors that represent the variability of these times and the sensitivity will vary with the relative levels of these main factors.

The correct number of trucks matched to the loader is essential for maximum efficiency of an earth-moving operation. For live operations, the plant match can be easily controlled by an experienced contractor. However, this may be a difficult task for operations that are only in the planning stage, because exact values of all the factors will not be known. As has been shown, plant match is sensitive to small changes in factor levels.

Despite the increase in load time, in certain situations extra bucketfuls per load are advantageous. This must never overload the truck for safety and plant longevity.

Spot and load pass time both have the same effect on the output. The 2^4 design has shown that the load pass time has the greatest effect on cost and production, for the chalk site referred to in the paper. As haul length increases, travel time will become the dominant factor. In both cases, keeping the component times to a minimum is essential if maximum production is to be achieved.

The simulation highlights the sensitivity of interactions between some factors and is therefore of value to those with only limited experience and expertise in earthmoving operations. Fig. 7(a), for example, indicates that if load pass time is reduced then production will not increase if the operation is already underresourced, such a decrease in load time should coincide with an increase in the number of trucks. Conversely, production will not increase simply by adding more trucks to the operation. These conclusions are fundamental to the efficient running of earthmoving operations but experience has shown that many contractors do not apply them in the field.

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APPENDIX I. MATCH FACTOR

The match factor is used to indicate how well the trucks and excavators are matched; i.e., whether the correct number of trucks has been allocated to give maximum efficiency. It is calculated using the following expression:

$$\text{match factor} = \frac{\text{number of haulers} \times \text{loader cycle time}}{\text{number of loaders} \times \text{hauler cycle time}} \quad (6)$$

The cycle times used in calculating the match factor must not include any idle times. A perfect operation is achieved when the match factor is one, although this is difficult to maintain due to "bunching" of trucks, i.e. the different speeds of the trucks will cause them to group together behind the slowest truck. A match factor greater than one indicates an overresourced operation (in terms of trucks); if it is less than one, the operation is underresourced.

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APPENDIX III. NOTATION

The following symbols are used in this paper:

e_i = effect of factor i on response;
e_{ij} = interaction effect between factors i and j on response;
$f(k)$ = response surface;
g = number of design points in experiment;
k = factor;
n = number of iterations of simulation for one design point;
P_i = production response at design point i;
r = number of factors in experiment;
s^2 = estimate of run variance;
$se_{(e)}$ = standard error of effect;
s_i^2 = estimate of variance of response at design point i;
$V_{(e)}$ = estimated variance of effect;
Y = system response;
ν_i = degrees of freedom of design point i; and
σ^2 = run variance.

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