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SCRAPER EARTH-MOVING FLEET OPTIMIZATION VIA SPREADSHEET-BASED MODELING

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ABSTRACT: Earth-moving operation has a great impact on the overall budget and schedule of any heavy civil projects. More often than not, the operational decisions are made largely based on field personnel's experience and judgment. In particular, decisions on earth moving operations by scraper-dozer fleets have been heavily influenced by the following belief: "The longer a dozer pushes a scraper for loading, the better earth-moving productivity is gained by the fleet." Even though there is some truth to this notion, scraper-dozer earth moving operations involve a much complex process that requires a systematic analysis for predicting the maximum production. To this end, this paper presents a spreadsheet-based scraper-dozer fleet operation model for its production optimization. Various optimization techniques, including a genetic-algorithm method, are presented for comparison and each technique's pros and cons are discussed.

Keywords: Spreadsheet-Based Modeling; Earth-Moving Operation; Optimization; Genetic Algorithm

1. INTRODUCTION

Use of scrapers in residential development and civil projects is a popular choice for earth-moving operation, which plays a great role in the projects' success in overall budget and schedule. It is, therefore, essential for project managers to maximize the productivity and the cost efficiency of the scraper fleet utilized in the projects. It is challenging, however, to achieve this because the successful management of scraper earth-moving operation does not come from individual utilization of the machines but from a collective managerial scheme. One of the reasons is that scrapers work in tandem with a dozer, which supports several scrapers to load soil and boost for takeoff as shown in Figure 1. In other words, unless these two types of machines work in an orchestrated way, it is not possible for projects to achieve the optimum productivity and efficiency.

Several studies [1-3] have been done to identify variables affecting productivity of the dozer-assisted scraper operations. Table 1 summarizes these variables, which includes various aspects of the scraper earth-moving operation: machine performance; field personnel skill; soil condition; job site condition; project planning; and maintenance program.

Figure 1. Scraper and Dozer Working in Tandem

• Haul-road conditions • Availability of motor grader to maintain haul-roads • Availability of labor to guide operators through the cut • Availability of labor to guide operators through the fill • Type of scraper • Type of pusher • Number of scrapers • Number of pushers • Safety considerations	• Supervision considerations • Availability of scrapers • Availability of pushers • Haul distance • Well laid out worksite & organized work plan • Well trained & briefed employees • Well maintained & serviced equipment • Ripping tight soils before scraping • Pre-wetting soil for easier loading • Equipment downtime • Type of loading • Operator ability

Table 1. Variables Affecting Scraper Earth Moving Operation [1-3]

Kuprenas and Henkhaus [4] developed an expert system-based tool for scraper selection and production for a set of given conditions, and Eldin and Mayfield [5] proposed an automated simple model to produce the number of scrapers and types. These models, however, did not consider the fact that the scraper load time is one single variable directly impacting both the productivity and the unit price of a scraper-dozer fleet [6]. The number of scrapers utilized in the scraper-dozer earth-moving operation is the main question for selecting the best scraper fleet. From a machine cycle time perspective, the most production influencing a cycle time component is a load time during which soil gets scraped and loaded into the scraper's bowl. This is not easy to determine because depending on the fleet size the optimum load time changes, contrary to the typical scraper field personnel's belief. The correct regulation of load time in the field can increase the production and lower the cost per yard of a scraper fleet.

Therefore, there should be a systematic way to predict this critical variable to maximize the scraping production. In this paper, variables affecting the pusher-scraper production are combined into an integrated scraper-dozer operation model. Then this model is represented in the spreadsheet program to predict the best scraper load time in the following two ways: a graphical method and a genetic algorithm method. These two methods predict the best fleet combination by optimizing the load time. The results of these methods and interpretations are discussed to provide pros and cons of each method from the perspectives of field operators and managers.

2. SCRAPER-DOZER OPERATION MODELING

Figure 2 shows a scraper-dozer operation model based on the machine performances, job site conditions, and acquisition. Each machine has its own processes through which a hourly rate ($/time), a productivity (unit/time), and an unit price ($/unit). For example, machines are used in a project through its own acquisition process, and their productivity numbers can be determined individually. However, the complexity comes from the fact that the scrapers and a dozer work together as shown in the overlapped area in Figure 2, making managers find a way to balance these two types of machines for the optimum use.

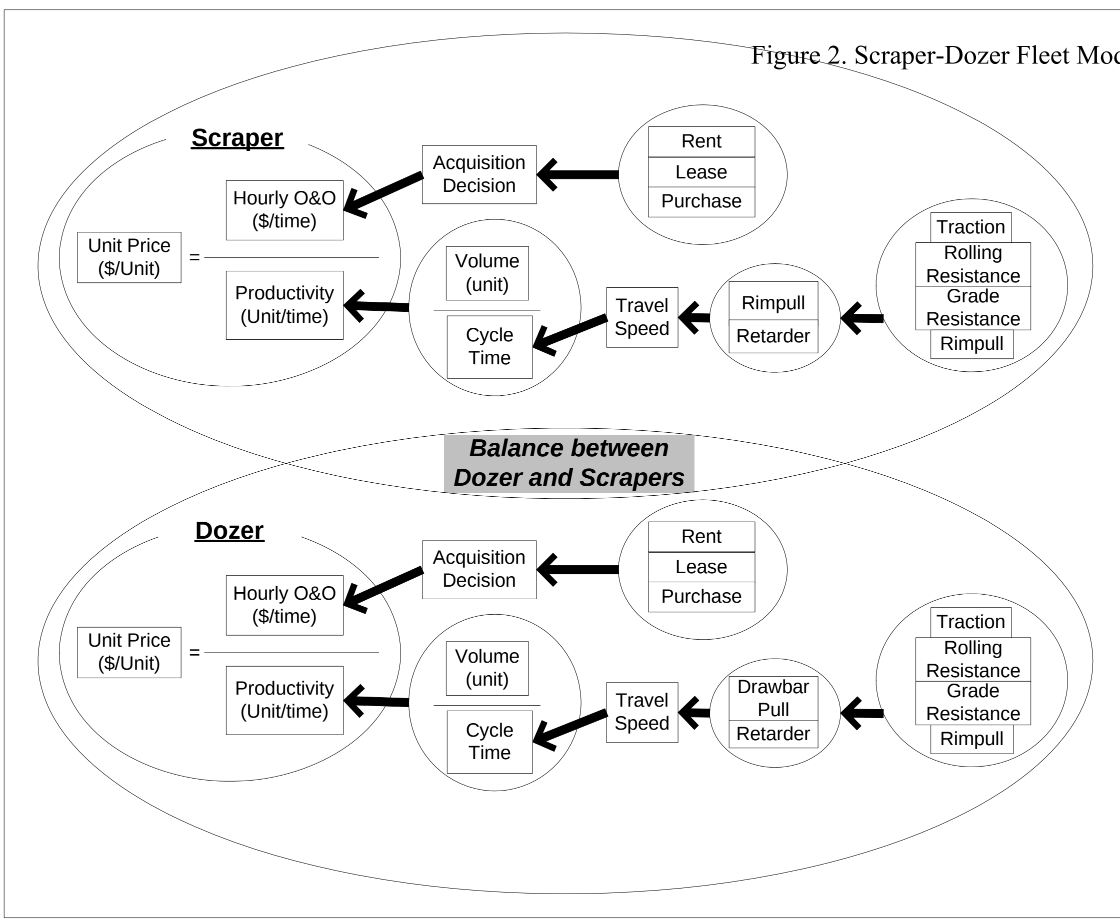


Figure 2. Scraper-Dozer Fleet Modeling

Productivity calculation for individual machines is performed as follows [7]. For scrapers, rolling and grade resistance values are determined from a site condition. A rimpull value is also determined based on the machine power and capability. Basically a rimpull value should be bigger than a total (rolling + grade) resistance value for the machine to move forward. If the total resistance is greater than the rimpull power, then it means the site condition is too adverse for the machine to function. A traction value represents another site condition that takes place between tires and the job site surface. When the rimpull overcomes the resistance but the surface does not provide enough traction (e.g. slippery condition or icy condition), again the machine cannot operate.

The rimpull and resistance values are used for the rimpull and retarder chart as shown in Figure 3 where the goal of these charts is to provide the travel speed given the machine capability and site condition. For flat and uphill situations, the rimpull should be the driving force overcoming the resistance, which is the situation where the rimpull chart (the left chart of Figure 3) should be used. In this situation, depending on the weight of the machine (itself and load weight), the speed of a scraper can be determined. If the scraper goes downhill (i.e. grade resistance > rolling resistance), the scraper's retarding system should be engaged, which qualifies for the use of the retarder chart (the right chart of Figure 3). In this chart, combining the gross weight and effective grade, the speed of the scraper can be estimated. Almost the same description can be applied for a dozer, drawbar pull is used instead of the rimpull.

Once the scraper's travel speed is determined, a cycle time can be calculated, and with the hauling capacity data, a productivity (= unit / time) value can be calculated in turn. Combining this productivity value with the hourly ownership and operation cost (= $ / time), the unit price (= $ / unit) can be determined as well.

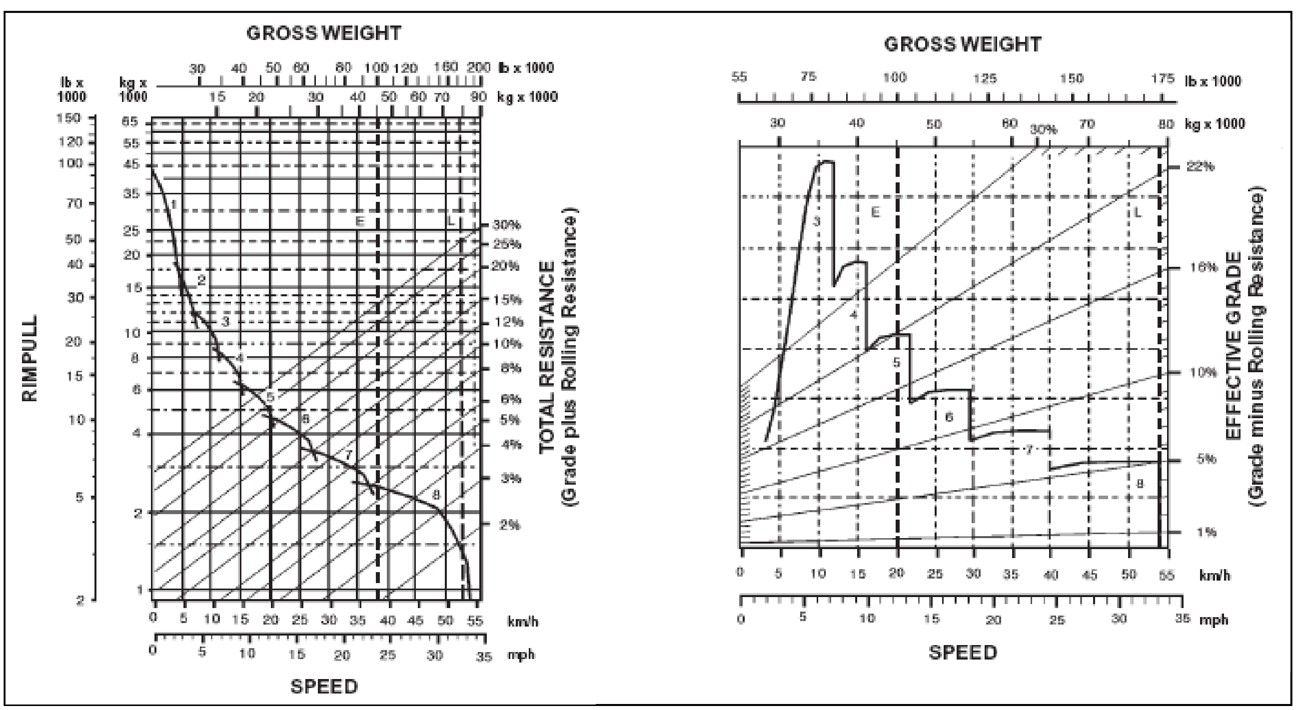


Figure 3. Scraper Rimpull Chart and Retarder Chart [7]

3. SPREADSHEET MODELING FOR OPTIMIZATION

Determining the productivity and unit price of individual machines in a scraper-dozer fleet is a relatively easy task; when they work together the same calculation cannot be separated and this situation takes more in-depth analysis.
In this section, this analysis is done in two different ways based on modeling in a spreadsheet program: graphical method and genetic algorithm method.

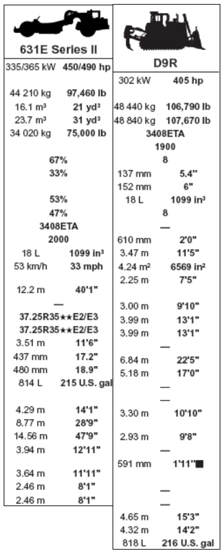
The following data is used for the example analysis for both methods.

Table 2. Example Data for Scraper/ Dozer and Site Condition

CAT D9N dozer	$243/hr
Dozer boost time	0.15 min
Dozer backtrack time	40% of load time
Dozer transfer time	0.1 min
CAT 631E scraper	$322/hr
Scraper transfer/ boost time	0.25 min
Scraper maneuver/ spread time	0.7
Hauling Distance	800 meter
Grade resistance	2%
Rolling resistance	4%
Payload (m^3/min^3)	(=7.8*T^3-33.3*T^2+48*T)

3.1 GRAPHICAL METHOD

The graphical method [6] determines the number of scrapers in the fleet by varying the load (or push-load) time, which is the most significant variable in the scraping operation in terms of impacting the fleet's productivity and unit prices. The first step is shown in Figure 4 in which, based on its performance and the given jobsite condition, the total cycle time of a scraper is determined where only the load time varies. The cycle time of a scraper is comprised of segments of time for: "push-load" → "boost" → "travel/haul" → "maneuver/ spread" → "return". The push-load time in conjunction with the payload formula produces the load growth curve, which is then turned to production rate. This production curve (at the lower-right corner of Figure 4) represents the theoretical productivity of one scraper for the various load time, assuming its production is not restrained by the dozer's capability.



Loading (LT)	?	Total Resistance: 6% (Uphill)
Time for Boosting (and Transfering)	0.25	4% RR/ +-2% GR
Time for Hauling(min)	2.4	Total Resistance: 2% (Downhill)
Time for Maneuvering and Spreading(min)	0.7	Hall Distance: 800 m
Time for Returning(min)	1.1	CAT D9 ($243/hr)
Cycle Time w/o Loading(min)	4.45	CAT 631 ($322.hr)

Load Time (min)	Cycle Time w/o Loading (min)	Total Cycle Time (min)	Payload (m3)	Production (m3/hr)
0.00	4.45	4.45	0.00	0.00
0.10	4.45	4.55	4.47	59.01
0.20	4.45	4.65	8.33	107.49
0.30	4.45	4.75	11.61	146.70
0.40	4.45	4.85	14.37	177.79
0.50	4.45	4.95	16.65	201.82
0.60	4.45	5.05	18.50	219.76
0.70	4.45	5.15	19.96	232.53
0.80	4.45	5.25	21.08	240.93
0.90	4.45	5.35	21.91	245.76
1.00	4.45	5.45	22.50	247.71
1.10	4.45	5.55	22.89	247.45
1.20	4.45	5.65	23.13	245.59
1.30	4.45	5.75	23.26	242.71
1.40	4.45	5.85	23.34	239.34
1.50	4.45	5.95	23.40	235.97

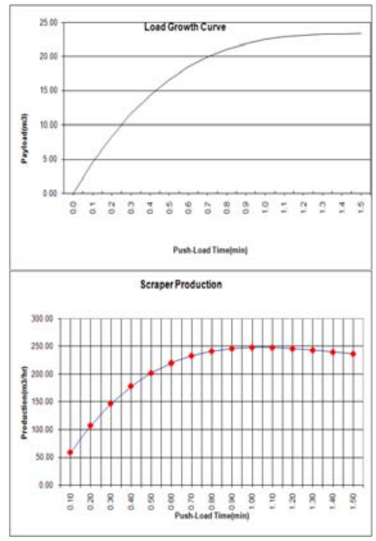


Figure 4. Scraper Production Calculation and Curve

For the dozer, almost the same process repeats to determine how much scraper production it can support. This is shown at the right-hand side of Figure 5 as labeled the pusher production. The dozer's cycle time consists of the following segments of time for: "push-load" → "boost" → "backtrack/ return" → "transfer/ position". Note that the payload amount for the dozer does not mean how much it can haul but how much it can help a scraper scrape soil into the bowl.

Loading (LT)	?
Boosting(min)	0.15
Backtracking/or Returning/or Maneuvering	40% Load Time
Transfering/or Positioning for Contact(min)	0.1
Pusher Cycle Time w/o Loading(min)	0.4*LT + 0.25

Load Time (min)	Cycle Time w/o Loading (min)	Total Cycle Time (min)	Payload (m3)	Production (m3/hr)
0.00	0.25	0.25	0.00	0.00
0.10	0.29	0.39	4.47	688.43
0.20	0.33	0.53	8.33	943.06
0.30	0.37	0.67	11.61	1040.02
0.40	0.41	0.81	14.37	1064.53
0.50	0.45	0.95	16.65	1051.58
0.60	0.49	1.09	18.50	1018.17
0.70	0.53	1.23	19.96	973.58
0.80	0.57	1.37	21.08	923.28
0.90	0.61	1.51	21.91	870.72
1.00	0.65	1.65	22.50	818.18
1.10	0.69	1.79	22.89	767.22
1.20	0.73	1.93	23.13	718.96
1.30	0.77	2.07	23.26	674.19
1.40	0.81	2.21	23.34	633.53
1.50	0.85	2.35	23.40	597.45

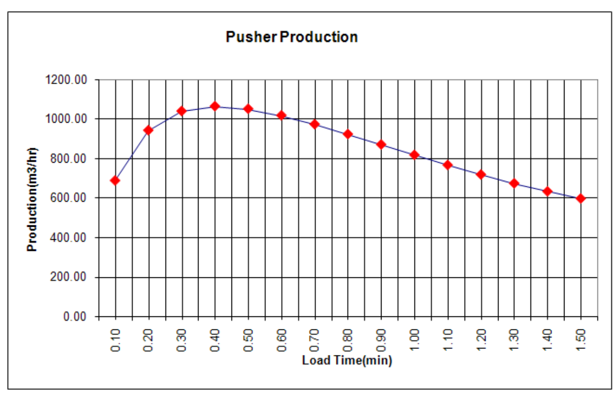


Figure 5. Scraper Production Calculation and Curve

ith these two production curves (from Figure 4 and 5), the total production of a group of scrapers can be theoretically calculated by multiplying one scraper production by the number of scrapers as shown in Figure 6 below. To provide realistic limit on the total scraper production, the dozer's production is overlaid (the thick curved line). Any scraper production numbers over the dozer's production curve is not possible in a real life because those values are beyond what the dozer can assist push-loading of the scrapers. Any scraper production under the dozer curve means that the dozer is under-utilized, meaning the fleet does not get the maximum output. As shown on the Figure, the maximum production is achieved at 1,064.5 m^3/hr at 0.4 minute of the push-loading time when 6 scrapers are used with a dozer. This is contrary to a field belief that the longer a dozer pushes a scraper for loading, the better earth-moving productivity is gained by the fleet.

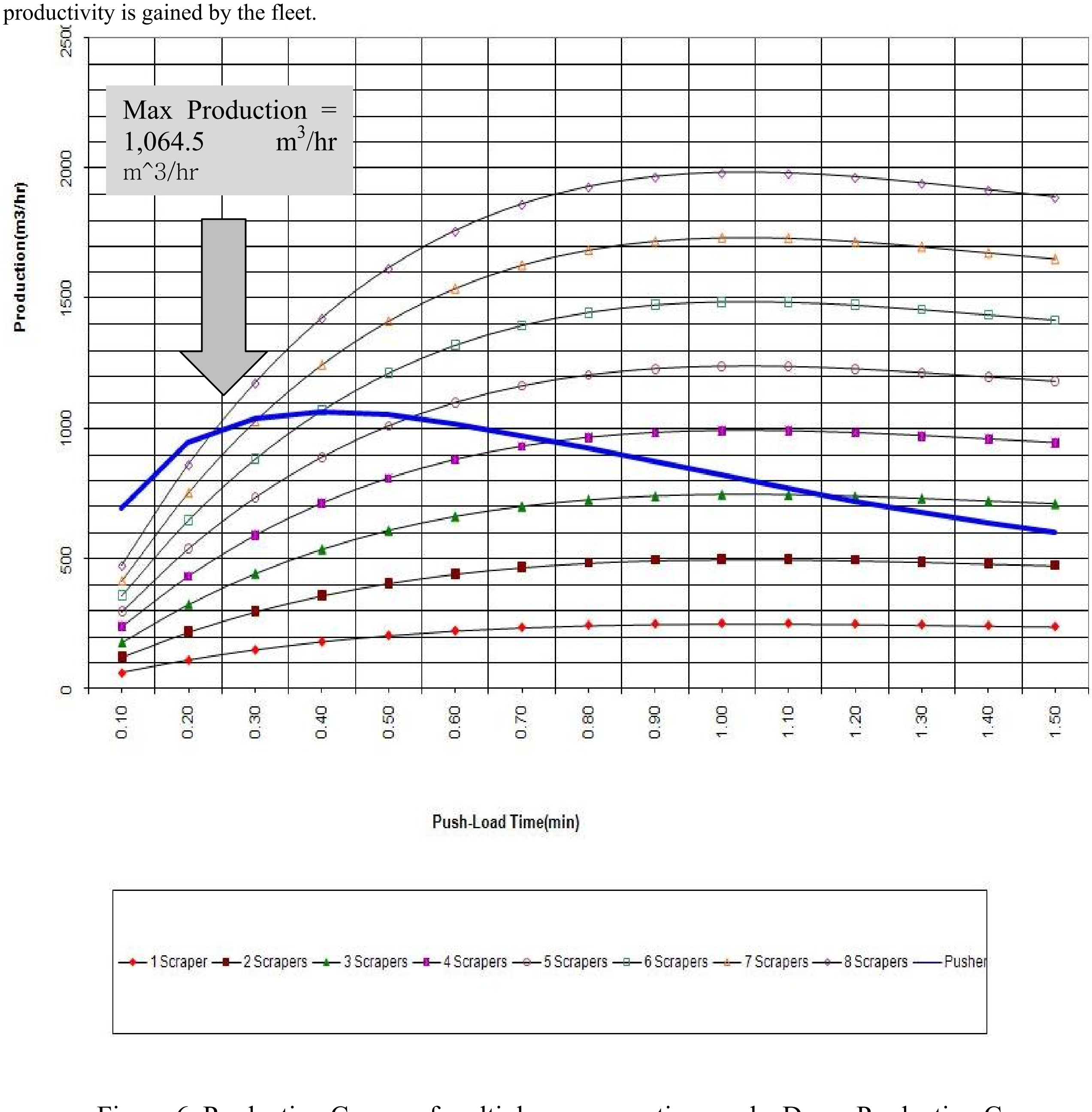


Figure 6. Production Curves of multiple scraper options and a Dozer Production Curve

Using these productivity values in Figure 6 and the hourly rates of the machines, the unit cost curves for the multiple scraper options are plotted in Figure 7. In this chart, interestingly enough, at 0.4 minute of the push-load time when the maximum production was achieved, the best unit cost is not achieved. Rather the best unit price is calculated to be 1.6 $/m^3$ when the push-load time is at 0.75 minute. Realistically, however, this is not a good push-load time a field operator wants to adhere to simply because the load time is slightly off this mark, the unit price will increase rapidly. From this point of view, the range of push-load time at 0.95 ~ 1.15 will be a better choice even though the productivity in this range will suffer.

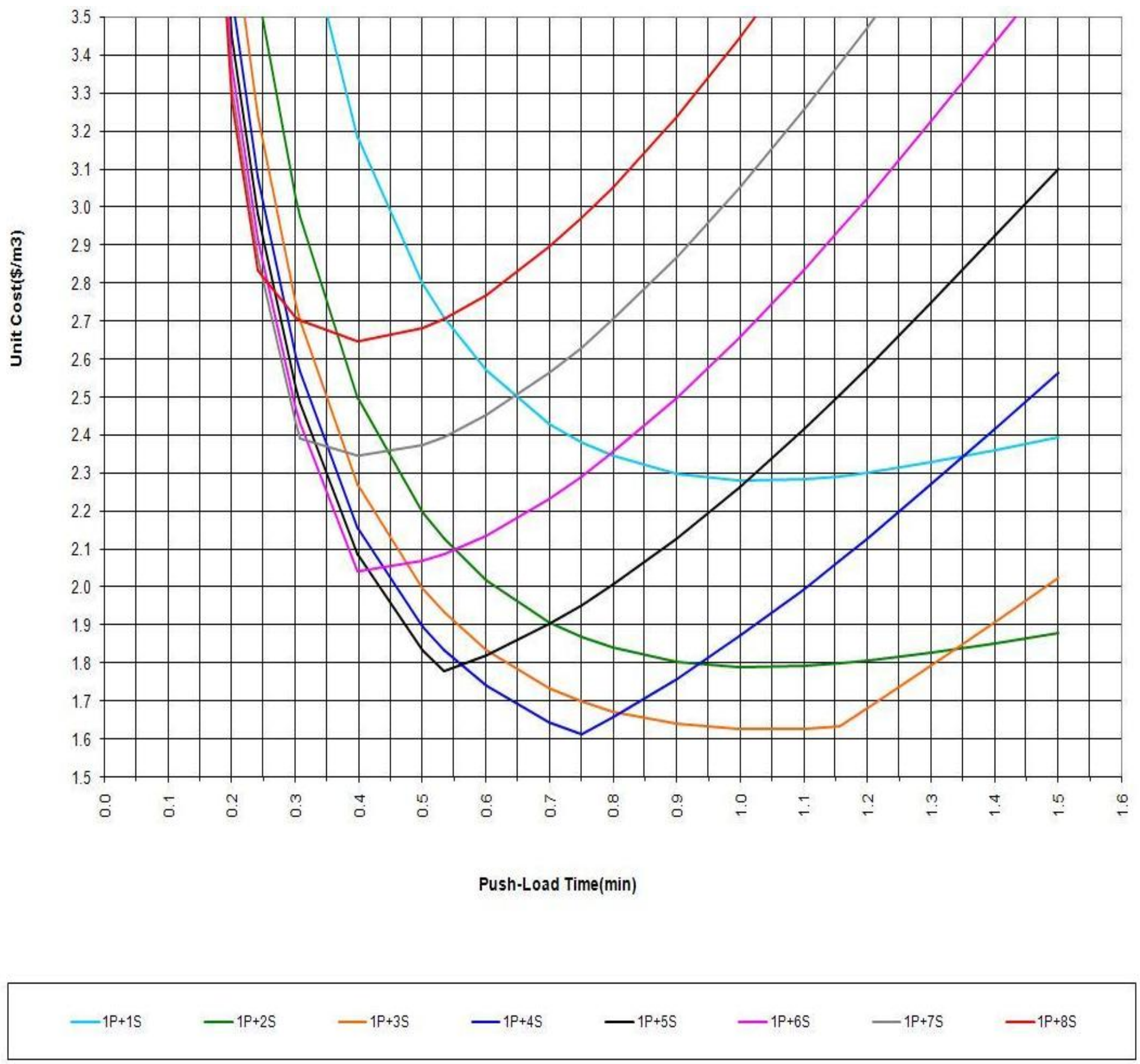


Figure 7. Unit Cost ($/m^3$) of the multiple scraper options

3.2 Genetic Algorithm Method

In this section, a GA (genetic algorithm)-based optimization tool, called Evolver by Palisade is used to find the best solution for the scraper-dozer fleet operation spreadsheet model. In a nutshell, the GA searches solutions by going through biological evolution: each solution passes along its good "genes" through "offspring" solutions so that the entire population of solutions continues to evolve better solutions as shown in Figure 8 [8].

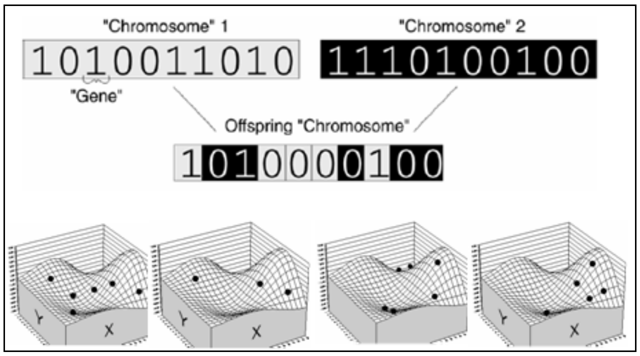


Figure 8. GA(Genetic Algorithm)-based solution process (Palisade)

Figure 9 shows theGA-based optimization solution process based on the same spreadsheet scraper-dozer model. One of the constraint conditions that need to be set up is the fact that total scraper production can not be greater than the dozer's. For the same project data, the GA-based solution provided the same optimum solution for the unit prices to be 1.6 $\$/m^3$ when the push-load time is at 0.75 minute.

3.3 Comparison

The two optimization methods, graphical and GA-based, provided almost the same answers. However, they have their own pros and cons. The graphical method provided more visually intuitive and insightful solutions than the GA method. The GA method can be easily setup on a spreadsheet model and it is capable of expanding to a multi-goal problem instead of focusing on a single goal problem solving.

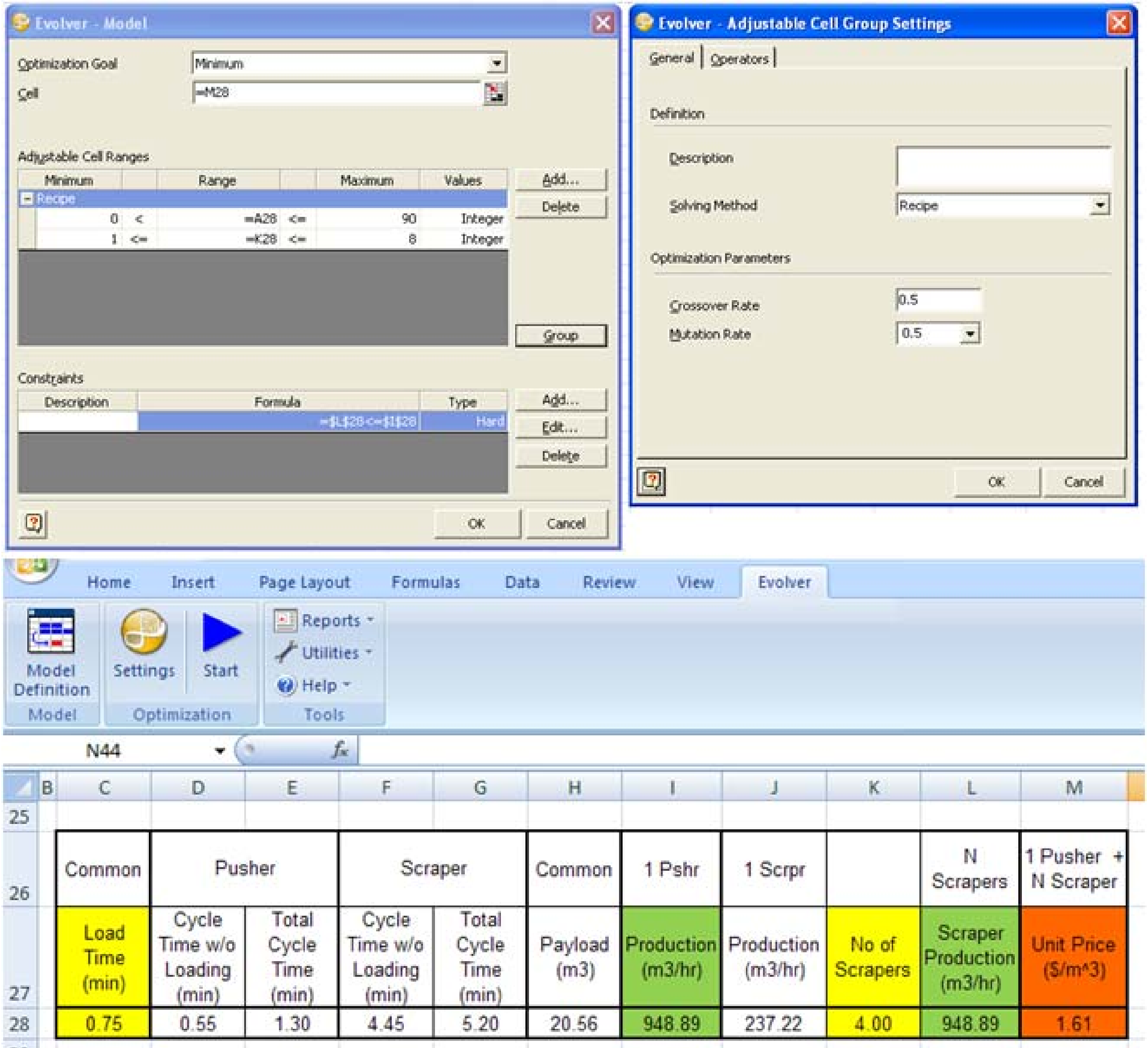


Figure 9. GA(Genetic Algorithm)-based optimization set-up and scraper-dozer fleet model solution

4. CONCLUSION

The earth moving operation has a great impact on the overall budget and schedule of any heavy civil projects. The decision on such operations should not be solely based on field personnel's experience and judgment. This article demonstrated how much the earth moving operation can be enhanced using systematic but simple modeling techniques on a spreadsheet format. To enhance the GA-based solution, however, the probabilistic approach is needed to reflect the realistic situation for the optimization analysis.

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