PRODUCTIVITY EVALUATION OF THE CONVENTIONAL AND GPS-BASED EARTHMOVING SYSTEMS USING CONSTRUCTION SIMULATION

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ABSTRACT
Over the past few decades, the construction industry has pursued productivity and quality improvement, enhanced safety, and reduced operational cost by applying geospatial data collection technologies. One solution, Global Positioning System (GPS) is being currently applied to earthmoving operations with several benefits over conventional systems in efficiency, performance, and safety. Basically, a GPS-based system provides a stake-less operation controlled by the operator who is on the vehicle. The operator is informed of information such as the amount of cut and fill volumes associated with precise elevations and the current location of equipment in real time. With these enhanced functions provided by GPS, the GPS-based system can achieve productivity improvement by the simplification of surveying tasks and reworks which are not required. However, planners and estimators have been struggling with the lack of data for evaluating GPS-based systems versus conventional systems prior to commencement of site work. The objective of this study is to present application models for evaluating performance of the conventional and the GPS-based systems using Web CYCLONE, a simulation methodology.

KEY WORDS
Earthmoving, Global positioning system, Simulation, Data collection.

INTRODUCTION
Earthmoving is a fundamental construction operation. Estimation or prediction of productivity of earthmoving operations has provided people in both academia and industry with an important subject for research. Over the past 100 years, earthmoving operations have used the same basic work procedures, such as surveying, staking, excavating, hauling, filling, and compacting. These work procedures have not changed much for a long time, even though there have been minor improvements to equipment technologies. Recently, digital control technologies developed in other industries have enabled the earthmoving equipment industry to devise a more efficient method for achieving great gains in efficiency and safety. The

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advent of Global Positioning System (GPS) technology has changed the mainstream of conventional work procedures. The GPS-based earthmoving systems were created based on digital control technologies, and have currently become the state-of-the-art in earthmoving. After GPS-based earthmoving systems were initiated on commercial construction equipment, clients and planners were confronted with an additional issue type of control conventional or GPS. Thus, an appropriate performance evaluation of the GPS-based system and a comparison of the performance by both systems, the conventional system and the GPS-based system, will be beneficial for planners in setting up an accurate plan and in controlling the performance.

EARTHMOVING OPERATION

Due to the characteristics of earth moving operations, the planning and performance of conventional earthmoving systems have been dependent on the skills and experience of site managers, equipment operators and surveyors. Rework, caused by their errors, is expensive, time-consuming, and unproductive. Surveyor tasks related to staking and checking the grades and operator skill levels determine the level of quality when using conventional systems. Before starting the operation, surveyors set grade stakes which give the basic visual guideline to equipment operators. They also reset stakes that have been knocked down frequently during operations. The task of restaking causes a significant delay because operators must hold the operation while surveyors recheck the grades and restake. On job sites where earthmoving has been executed, it has been observed that operators proceed with the operation without any resetting of stakes because surveyors do not always stay on sites, except for large-scale projects. This causes serious deviations from the desired design surface and rework sometimes follows. This is very expensive, time-consuming and unproductive.

In order to reduce the impact of human factors, a number of studies and development efforts have been undertaken to automate conventional excavation and grading operations. The GPS-based earthmoving system, which combines real time GPS positions with 3-D graphic displays, was first created and developed in the mining industry and is currently in use in the construction industry (i.e. earthmoving operations). The GPS-based earthmoving system is based on the concept that operators can work without any stakes during operation. A GPS antenna and receiver which are mounted on the equipment receive GPS signals from satellites and transfer them to the installed computer unit. The transferred signal shows the real-time location of the target equipment on a map formulated with graphic files. Once the operation starts, these devices monitor the progress of the equipment and guide the operators. This function allows the operator to know the position of the equipment and the volume of soil moved in real time. Accordingly, GPS enables three-dimensional models of the work in progress to be updated in real time, assisting the operator to move the earth more efficiently. According to the manufacturer’s references, GPS-based systems supply high efficiency yielding labor cost savings and achieving high accuracy. The conventional system is more efficient in situations requiring flexible tolerance and on small-scale projects that do not support the high initial costs of a GPS-based solution.
SIMULATION METHODOLOGY

This study utilized the Web CYCLONE simulation program, an on-line web based program that uses CYCLONE (CYCLic Operation Network) methodology. The program simplifies the simulation modeling process and makes it accessible to construction practitioners with limited simulation background.

FRAMEWORK FOR SIMULATION MODELING

This study intends to demonstrate the influence on performance of the GPS-based earthmoving operations in comparison with those of a conventional and a GPS-based systems. Accordingly, the specific construction site conditions and the construction simulation required to reflect them be modeled using the same assumptions and conditions.

The proposed site conditions used as the framework are presented as shown in Figure 1. The following assumptions were made for the modeling:

- All site conditions such as soil condition, hauling road conditions, and all equipment conditions are assumed to be the same in the GPS-based system and conventional systems.
- One working day consists of 8 working hours.
- Effective working hours are 50 minutes per hour.
- The resources in ground are initialized in a large amount (e.g. GEN 30) at the beginning of the simulation.

![Figure 1: Proposed Site Conditions for Simulation Modeling](image-url)

Figure 1: Proposed Site Conditions for Simulation Modeling
**DATA COLLECTION**

In order to run the simulation, the framework, including the strategy of equipment selection, allocation of construction equipment, and duration of each activity need to be determined. Accordingly, the information pertaining to the time of restaking, grade checking, and even the probabilities of restaking was derived from an interview survey with site personnel working with four projects using either conventional or GPS-based system. These projects were located in Indiana and Illinois. The rest of the information, such as the cycle time and cost for particular equipment pieces, were found in standard references (e.g. Caterpillar performance book and R.S. Means).

The duration of each work activity, the specification of equipment, and number of resources based on the interview survey and literature references are shown in the simulation diagrams of Figures 2 through 5.

Equipment operating and labor costs were found using RS Means data. They were derived by multiplying hourly output by the labor and equipment unit costs. In the conventional system, these calculated costs are assumed to be hourly equipment and labor costs. The additional costs of GPS instruments were added in the GPS-based system. The GPS-based system needs two instruments; the machine cab system which receives the GPS signal from the base station, and a base station which is capable of receiving and transmitting differential GPS signals to each vehicle. The costs of the machine cab system are added onto hourly operating costs of each piece of equipment and the costs of the base station are added onto the total hourly operating costs of the GPS-based system. According to the vendors, the rental cost per 10 months of a base station is estimated at $20,000 and that of the machine cab system for dozer or grader at $50,000. (Trimble, 2001)

Table 1 shows the specification of each piece of equipment and the hourly costs including the equipment operation costs and the labor costs for each resource used in the simulation.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Conventional system</th>
<th>GPS-based system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dozer (CAT D7G)</td>
<td>143</td>
<td>176</td>
</tr>
<tr>
<td>Loader (CAT 972)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Truck (CAT D30D)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grader (CAT 14H)</td>
<td>119</td>
<td>153</td>
</tr>
<tr>
<td>Surveyor (3 crews)</td>
<td>102</td>
<td></td>
</tr>
<tr>
<td>Base station</td>
<td>13</td>
<td></td>
</tr>
</tbody>
</table>

**CONSTRUCTION SIMULATION**

**COMMON ASSUMPTIONS**

One of the advantages provided by the GPS-based system is a stake-less operation. The conventional system requires the additional tasks of setting and resetting the grade stakes, which were often knocked down during excavating, stockpiling, or grading. As a result of the interview survey, it was found that 4 times out of 100 dozing operations are interrupted by surveyors who must reset the grade stakes that were knocked out. The rest of the time, the
dozing operation goes ahead without any interruption or by ignoring the small numbers of the grade stakes that were knocked down. These interview results also indicated that the probability of resetting stakes was 7 times out of 100 grading operations. These probabilities will be applied to reflect the site conditions being simulated.

According to the results of the investigation of job sites and interviews with site personnel, the conventional system generally required additional work tasks. The tasks were data logging, which is conducted at the end of each sift, surveying and grade checking, which is done before starting the shift. These additional tasks took approximately 40 minutes for each eight hour shift.

**SIMULATION MODELING**

A simulation model was assumed to be a two link system consisting of dozer and grader because dozer is the most economical type of mobile construction equipment when working a 300 ft haul distance. This assumption is based on information in standard equipment performance handbook. (Caterpillar, 2003)

The conventional system required the task of resetting stakes during dozing and grading operations. Surveyors were needed as additional resources to accomplish these additional tasks. These additional tasks and resources required in the conventional system were not required in the GPS-based system due to the technical characteristics of automatic grade checking and a stake-less operation. Figures 2 and 3 show the CYCLONE models for each system.

![Simulation Modeling of GPS-based System](image)

**Figure 2: Simulation Modeling of GPS-based System**
Simulation results with a fixed number of resources based on the assumptions described above are given in Table 2. In order to assess the difference between the conventional and the GPS-based system, comparison rates are presented as well. The comparison rates are percentage rates derived by dividing the value of GPS-based system by that of conventional system.

As a result of running a simulation, the hourly productivity in cycles/hour was calculated based on 60 minutes per hour as operating time. In this study, operational efficiency needs to consider 50 minutes per hour. When estimating the daily productivity, 40 minutes for each 8 hour shift for the additional tasks which were required in the conventional system was used. Accordingly, the adjusted hourly productivity was derived by dividing daily productivity by 8 hours.

Table 2 indicates that 26.02 (cycles/50min.) of the adjusted hourly productivity of the conventional system were derived from the equation as shown below.

$$ \frac{26.02 \text{ (cycles/50min.)}}{28.92 \text{ (cycles/50min.)} \times \frac{7.2 \text{ hours/day}}{8 \text{ hours/day}}} $$

A correction factor 7.2 used on the equation described above reflected actual working hours which 40 minutes for each 8 hours shift were considered in (i.e. 7.2 hours/day = 7 hours + [1 hour - (40 min. / 50min.)]).

Based on Table 1 showing equipment and labor costs, the GPS-based system required additional costs for a base station which was installed one per project. Accordingly, $13.33 for the hourly operation cost of the base station needed to be added onto the total hourly cost.
of the GPS-based system. For an example shown in Table 2, 15.04 ($/cycle) of the adjusted unit cost of the GPS-based system was derived from the equation as shown below.

\[
15.04 \text{ ($/cycle)} = \frac{518.23 \text{ (hourly cost)}}{34.48 \text{ (cycles/50min.)}}
\]

$518.23 of hourly cost was derived by adding $13.33 of the hourly cost for a base station to $505.02 of hourly cost for the equipment and the labor costs.

### Table 2: Simulation Results

<table>
<thead>
<tr>
<th>System</th>
<th>Hourly Prod. (cycles/50 min)</th>
<th>Daily Prod. (cycles/day)</th>
<th>Adj. Hourly Prod. (cycles/50min)</th>
<th>Hourly cost</th>
<th>Unit Cost ($/cycle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conv</td>
<td>28.92</td>
<td>208.19</td>
<td>26.02</td>
<td>507.00</td>
<td>19.48</td>
</tr>
<tr>
<td>GPS</td>
<td>34.48</td>
<td>275.80</td>
<td>34.48</td>
<td>518.23</td>
<td>15.04</td>
</tr>
<tr>
<td>Rate(%)</td>
<td>119.23</td>
<td>132.48</td>
<td>132.48</td>
<td>102.24</td>
<td>77.17</td>
</tr>
</tbody>
</table>

### OVERALL RESULTS

It has been shown that the GPS-based system is 32.48% more productive when compared with the productivity of the conventional system. Pertaining to the unit costs ($/cycle), the GPS-based system has 22.88% (i.e. 22.88% = 100% - 77.17%) lower cost.

### SENSITIVITY ANALYSIS

Sensitivity analysis of the simulation provides an opportunity to see the various influences of resources on performances. The objective of sensitivity analysis is to optimize the performance of the given system by varying the number of resources and identifying the factors affecting the result.

The resource units were initialized and varied as presented in Table 3.

### Table 3: Units of Various Resources

<table>
<thead>
<tr>
<th>System</th>
<th>Node no.</th>
<th>Resources</th>
<th>Min. units</th>
<th>Max. Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>19</td>
<td>Dozer</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>Grader</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>Surveyor</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>GPS</td>
<td>19</td>
<td>Dozer</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>Grader</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

A sensitivity analysis indicates that the number of dozers is the critical factor causing varying productivity. The varying number of graders associated with the number of dozers does not affect the productivity until 3 dozers are operating.

Based on Table 4, it is noticed that the combination composed of 5 dozers and 2 graders in 15 scenarios of the GPS-based system and the combination composed of 4 dozers, 1 grader and 1 surveyor in 30 scenarios of the conventional system, yield the lowest unit costs. The combination composed of 5 dozers and 3 graders of the GPS-based system and the combination composed of 5 dozers, 3 graders and 2 surveyors of the conventional system, allow the highest productivity. However, the unit costs of the former scenario are lower than the latter. Thus, the cases having the lowest unit costs may be generally efficient operations.
and the cases having highest productivity with low unit costs can be applicable in situations where time is more critical than cost.

Table 4 shows the three cases having the lowest, the medium and the highest unit costs in the GPS-based system. In order to have the consistent comparison rates, the same cases of the conventional system were compared with those of the GPS-based system. Values of average and standard deviation were calculated with considerations of all scenarios.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Equipment</th>
<th>Unit Cost ($/cycle)</th>
<th>Adj. Hourly Prod. (cycles/50min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dozer</td>
<td>Grader</td>
<td>Conv. GPS</td>
</tr>
<tr>
<td>Best</td>
<td>5</td>
<td>2</td>
<td>16.70</td>
</tr>
<tr>
<td>Medium</td>
<td>4</td>
<td>1</td>
<td>19.14</td>
</tr>
<tr>
<td>Worst</td>
<td>1</td>
<td>3</td>
<td>49.49</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>84.31</td>
</tr>
<tr>
<td>Std.</td>
<td></td>
<td></td>
<td>8.99</td>
</tr>
</tbody>
</table>

The simulation results indicate that the comparison rates of the adjusted hourly productivity and the unit costs are 129.90 % and 84.31 %, respectively.

The fact that the unit costs of the GPS-based system are lower than those of the conventional system is due to the higher hourly productivity of the GPS-based system. Therefore, the high initial costs of the GPS-based system can be offset by the higher productivity and the lower unit costs of the GPS-based system on large-scale projects with long construction periods. This fact also indicates that the conventional system is still applicable to a small-scale project.

**CONCLUSIONS**

This study has addressed the framework and methods for achieving a performance evaluation of GPS-based systems and presented the simulation models associated with site investigations and an interview survey.

Throughout the study, it is noted that GPS-based system is more efficient than the conventional system based on assessment of hourly productivity and unit costs. Planners need to assess the profit estimated with good performance and to compare it with the high initial cost of GPS devices prior to commencing of site work.

For a more precise evaluation of the GPS-based system, more economical concerns have to be reviewed. The benefits provided by the GPS-based system such as reduced rework, faster response to changes and soil volume checking should be converted to economical values to be assessed in the total evaluation. In addition, effects of the reduced rework provided by the accuracy of GPS needs to be assessed in detail.

The method based on simulation model suggests one of a number of methods which can be used to evaluate the performance of the conventional and the GPS-based systems. It is also shown that sensitivity analysis can be used to find the most optimal scenario over a range of varying working conditions. The results of this study provide a framework which enables the planner to establish a strategy of system selection, fleet management, and site management.
REFERENCES


