연구논문

Software for Simulating Open-pit Truck/Shovel Haulage Systems using Google Earth and GPSS/H

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구글어스와 GPSS/H를 이용한 노천 채광장의 적재−운반 시뮬레이션 소프트웨어 개발

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요 약 : 본 연구에서는 노천 채광장의 적재-운반 시뮬레이션을 수행할 수 있는 새로운 소프트웨어(GEMISIMS)를 개발하였다. 구글어스, Keyhole Markup Language(KML), 수정된 최적경로 분석 알고리듬, GPSS/H 시뮬레이션 언어를 유기적으로 결합할 수 있는 시스템 구조를 설계하였고, GEMISIMS 소프트웨어의 구현을 위해 사용하였다. 사용자는 GEMISIMS 소프트웨어를 이용해 적재지점과 덤핑지점 사이의 최적 운반경로를 분석할 수 있으며, 시뮬레이션을 통해 운반 경로별로 투입되어야할 최적의 트럭 수를 결정할 수 있다. 또한, 트럭의 이동과 관련한 시뮬레이션 결과를 구글어스 3차원 뷰어(viewer)를 통해 시각적으로 확인할 수 있다. 본 논문에서는 GEMISIMS 소프트웨어의 개발 방법을 설명한 후, 인도네시아의 석탄 노천광산을 대상으로 수행한 사례연구 결과를 제시한다. 개발된 소프트웨어가 노천 채광장의 적재-운반 시스템을 이해하는데 효과적으로 활용될 수 있을 것이라 기대한다.

주요어 : 노천광산, 운반작업, 구글어스, KML, GPSS/H

Abstract : This study presents new software, named Google Earth-based MIning SIMulation System(GEMISIMS), to simulate a truck/shovel haulage system in open-pit mines. System architecture using Google Earth, Keyhole Markup Language (KML), a modified least-cost path algorithm and the GPSS/H simulation language was suggested and used for the implementation of GEMISIMS. GEMISIMS allows users: (1) to determine optimal haulage routes of trucks between shovels and dumps(or ore stockpiles), (2) to optimize the number of trucks which will be allocated to each route and (3) to animate the movements of trucks using the 3D render window of Google Earth. This paper reports the concept and details of the software development and its application to an open-pit coal mine in Indonesia which revealed that GEMISIMS can support the better understanding of an open-pit truck/shovel haulage system.

Key words : Open-pit mine, Haulage operation, Google Earth, KML, GPSS/H

Introduction

With the advent of the Internet, Google Earth (GE) becomes a popular visualization tool in many fields

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and plays an increasingly important role not only for private users in daily life but also for scientist, practitioners, policy-makers and stakeholders in research and application (Boulos, 2005; Patterson, 2007; Chen et al., 2009; Sheppard and Cizek, 2009; Wright et al., 2009; Yamagishi et al., 2010; Ballagh et al., 2011, Chien and Tan, 2011; De Paor and Whitmeyer, 2011; Postpischl et al., 2011; Tomaszewski, 2011; Webley, 2011). GE reads and displays the Keyhole Markup Language (KML) files. KML was initially created in 2001. It has evolved to its status as an international standard authorized by the open geospatial consortium (http://www.opengeospatial.org).

KML enables users to add custom data to GE and to share any geo-referenced information on the Earth's surface. The structure of KML has been documented by Wilson et al. (2008) and Wernecke (2009).

In response to the increased use of GE, several applications have been recently developed in the mining industry. Nieto et al. (2010) developed the Assisted Driving System (ADS) for haulage trucks operating in open-pit mines using GE. The ADS includes Global Positioning System (GPS), a wireless communication network, a truck driver's fatigue detection system and an enhanced visibility display. Thus, it can trace the movements of trucks and provide real-time proximity warning to reduce accidents related to low visibility conditions (Sun et al., 2010a; Sun et al., 2010b). Choi and Nieto (2011) presented an application of GE for optimal haulage routing of dump trucks using Modified Least-Cost Path Algorithm (MLCPA). It can determine optimal haulage routes between shovels and dumps that ensure the least travel time or fuel consumption of trucks and can effectively visualize the routes using a 3D render window of GE and KML. These previous studies demonstrate the potential of GE as a tool for open-pit mining operations. However, relatively little attention has been paid to integrating the capabilities of GE with mining simulation techniques to support better understanding of an open-pit truck haulage system.

There have been many studies in simulating an open-pit truck/shovel haulage system for improving the efficiency of haulage operations (Hauck, 1979; Topuz and Duan, 1989; Bonates, 1996; Temeng, 1997; Blackwell, 1999; Aksoy and Yalcin, 2000; Alarie and Gamache, 2002; Niemann-Delius and Fedurek, 2004; Oraee and Asi, 2004; Choi et al., 2007; Yan and Lai, 2007; Krause and Musingwini, 2007; Zhang, 2008; Osanloo et al., 2008; Choi et al., 2009a; Ercelebi and Bascetin, 2009; Newman et al., 2010; Choi, 2011). The history of simulation techniques used in the mining industry is well reviewed by Sturgul (1996). In particular, Choi (2011) shows how the GPSS/H simulation language (http://www.wolverinesoftware.com/) can be effectively applied to problems in mining operations. GPSS/H is a low-level and nonprocedural language designed for studying systems represented by a series of discrete events. Therefore, GPSS/H is suitable to simulate an open-pit truck/shovel haulage system (i.e., a cyclic queue) where a single shovel loads each truck,

and the trucks travel to dumping areas, and then they return to the shovel. Furthermore, GPSS/H is efficient, very fast, widely available, continually being upgraded, and has proven to be extremely versatile for mining related operations (Sturgul, 1996).

This study presents new software, named Google Earth-based MIning SIMulation System (GEMISIMS), which has been developed using GE, KML, MLCPA and the GPSS/H simulation language. The concept and details of the software development and its application to an open pit coal mine in Indonesia are reported in this paper.

Modified Least-Cost Path Algorithm

MLCPA, developed by Choi and Nieto (2011), is a spatial optimization algorithm to determine optimal haulage routes of off-road dump trucks. In the raster-based grid data structure, area is divided into rows and columns which form a regular gird matrix structure by setting the cell dimensions. Each cell within the grid matrix contains location coordinates as well as an attribute value. To analyze least-cost paths on a raster surface, a virtual network should be constructed under two conditions: (1) the centers of each grid cell serve as the nodes in the network and (2) the connections between neighboring grid cell centers act as the links of the network. Once the virtual network is established, a source cell (where Dijkstra's (1959) algorithm will be initiated) should be identified. A destination to which off-road dump trucks will move for haulage operations is generally selected as the source cell, having an accumulated cost of zero. Eight neighborhood cells are searched from the source cell and examined to calculate costs of passing from the cells to the source cell using a cost map.

The cost map is a raster data set in which the value associated with each cell represents the cost (e.g., time, fuel consumption, dollar cost, or risk) per unit length of passing through the cell. It can be generated from a land-use map by correlating land-use classifications such as paved road, unpaved area, dumping area, etc. with in-situ measurement data of off-road dump trucks such as speed, travel time or fuel consumption at different land-use conditions. The cost function determines a weighted distance (i.e., the cost of passing) between neighboring grid cell centers

instead of calculating an actual physical distance. Once the costs of passing from eight neighborhood cells to the source cell are calculated using the cost map and the cost function, Dijkstra's algorithm is initiated and determines one neighborhood cell having the least accumulated cost of passing to the source cell.

The determined cell assigned the least accumulated cost is confirmed and then is defined as a current cell. From the current cell, another search of its eight neighborhood cells is started to find unconfirmed cells, and the costs of passing from the unconfirmed cells to the current cell are calculated using the cost map and the cost function. This optimization process is repeated until every cell in the raster-based grid data structure has the least accumulated cost of passing to the source cell and is confirmed. When the optimization process is finished, each cell has two attributes: the least accumulated cost of passing to the source cell and a pointer indicating the direction which an off-road dump truck should move to trace the least-cost path. Finally, the least-cost paths between origins (loaders) and destinations (dumps or stockpiles) which off-road dump trucks will take are generated as optimal haulage routes.

System Architecture

Fig. 1 shows the system architecture of GEMISIMS. GEMISIMS is written in Visual Basic.NET 2008 and operates on IBM PCs under the Microsoft Windows platform (i.e. XP, Vista & 7). An open-source ActiveX control provided by the Google-Earth-Airlines (http://www. googleearthairlines.com) was used to embed a 3D render window of GE into GEMISIMS. This ActiveX control activates the interaction between GE COM API and GEMISIMS. GEMISIMS provides users with the basic functionalities of GE for visualizing data using the embedded 3D render window with true-color satellite images. In addition, GEMISIMS has a capability to generate KML files related to objects such as dumps, ore stockpiles, shovels, trucks and routes in an open-pit truck/shovel haulage system. These KML files are utilized to draw the objects in the 3D render window and to share them with other users.

MLCPA is fully implemented within GEMISIMS. Therefore, users can determine optimal haulage routes
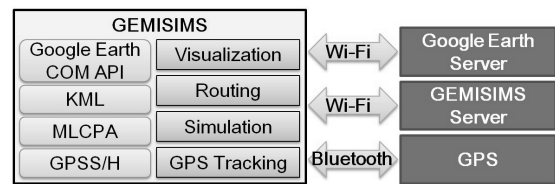

Fig. 1. System architecture of GEMISIMS.

between loading and dumping points for haulage operations. GEMISIMS can generate an input file of GPSS/H for simulating an open-pit truck/shovel haulage system according to users' requirements. Once the input file is ready, GEMISIMS activates the executable of GPSS/H to run simulations, and then performs post-processing to extract useful information from the output file of GPSS/H. GEMISIMS is also coupled with a truck-mounted GPS using the Bluetooth technology (http://www.bluetooth.com). Thus, it can dynamically visualize and update the GPS tracking data of trucks.

The GEMISIMS server is used to manage data files. It allows sharing and synchronization of the data files among multiple GEMISIMS clients. Since any data files updated by a GEMISIMS client can be shared with other GEMISIMS clients in real-time using wireless networks, it can significantly improve the dissemination of dispatching information to all truck drivers involved in a haulage work. Many commercial server solutions are available to construct the GEMISIMS server. This study selected the Dropbox server (http://www.dropbox.com) that is a free online data-sharing and synchronization solution.

Fig. 2 illustrates data files managed by the GEMISIMS server. Information related to the user's account, mining site, absolute references to all data files used in the project, coordinates system, fleet of trucks, time and fuel studies of trucks, and dispatching schedule are recorded as Comma-Separated Values (CSV) files. The Network Link element in KML allows a hierarchy of KML files linked to each other in a tree-like structure. A source (parent) KML file can activate GEMISIMS to fetch the linked files such as Portable Network Graphics (PNG) image, single KML and multiple KML files. Next, GEMISIMS loads them into memory and displays them in the 3D render window. The fetched (child) KML files can also contain links to other KML files.
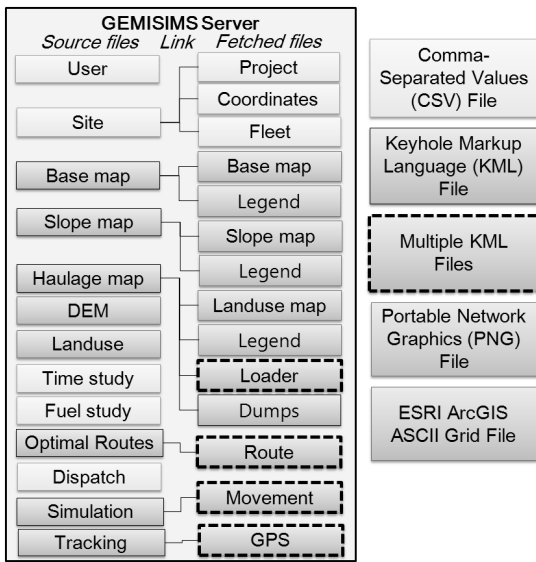
Fig. 2. Data files managed by the GEMISIMS server.

When the fetched KML files are loaded into memory, the Network Link element can refresh them using time-based parameters such as the RefreshInterval in KML. The Digital Elevation Model (DEM) and Landuse files are used to determine optimal haulage routes using MLCPA.

Software Development

GEMISIMS's functionalities are organized into six broad categories: server login, project information, map visualization, route optimization, mining simulation and GPS tracking. These six broad categories are reflected in the user interfaces of GEMISIMS (Fig. 3). When an authorized user logs in to GEMISIMS, the main user interface with the 3D render window appears on the screen. Based on the user's selections at the category of project information, data files related to the coordinates system are loaded into memory. Next, information about the truck model, driver and GPS availability of the truck are displayed on the interface status bar at the bottom of the 3D render window.

GEMISIMS displays an open-pit mining site using the 3D render window. Therefore, high-resolution satellite images draped over a DEM can be displayed in conjunction with KML files that represent the mine's base map,

Fig. 3. Login (Top) and main (bottom) user interfaces of GEMISIMS.

slope map, land-use map, and locations of shovels, ore stockpiles and dumps. In particular, the Ground Overlay element in KML is utilized to define the boundaries of base, slope, and land-use maps in terms of latitude and longitude, the rotation of the maps around their center (degrees, a counterclockwise direction), and the altitude of the maps (m a.s.l.). Since the Screen Overlay element in KML indicates a 2D image fixed to a specific location on the screen and is unaffected by navigation around or movement of the Earth model, it is used to display a map legend. GEMISIMS utilizes the Placemark element in KML, which can specify a 2D image or a 3D model as a custom icon and allows for the use of Hyper Text Markup Language 5 (HTML 5), to describe the information of shovels, ore stockpiles and dumps.

When the user activates the button for optimization, a new user interface, designed to apply MLCPA, appears on the screen (Fig. 4). The user can select an objective

function (either travel time or fuel consumption) and a truck model, and then can review three charts that show in-situ measurements of the selected truck's performance at a mining site: the upper chart shows the speed (km/hour) or fuel consumption (liter/100km) of loaded and empty trucks at different land-use conditions, and the middle and lower charts illustrate graphs of the vertical factor regarding terrain relief and the horizontal factor related to curves along a route respectively. In addition, the user can choose all or subsets of shovels (loaders), dumps and stockpiles as origins and destinations in optimal haulage routing of trucks. Three options of the haulage type (i.e., single trip of a loaded truck, single trip of an empty truck and round trip with the fixed assignment) are provided. The first and second options are useful in a variable truck dispatching system, where new origins and destinations are dynamically assigned into loaded and empty dump trucks during haulage oper-ations. The third option can be effectively used in a fixed truck dispatching system, where loaded and empty trucks use same haulage route between origins and destinations. When the user activates the OK button, the optimization is performed using MLCPA, and then optimal haulage routes are saved as KML files and displayed on the 3D render window. The details of the optimi-zation process are described in Choi and Nieto (2011).

GEMISIMS enables the user to determine the optimal number of trucks which will be allocated to a haulage route between a shovel and a dump (or an ore stockpile) by simulations. For the simulations, the user should define following input parameters: (1) number of trucks to simulate for, (2) number of shifts to simulate for, (3) initial truck dispatch interval(min), (4) profit per load($), (5) fixed cost(including the operating cost related to shovels) for the mine per shift ($/day), (6) costs for each truck per shift ($/day), (7) wages per a truck driver per shift ($/day), (8) minutes of work per shift, (9) spotting time of trucks at the shovel (min), (10) loading time of the shovel (min), (11) travel time of loaded trucks along the haulage route (min), (12) spotting and dumping time of trucks (min) and (13) travel time of empty trucks along the haulage route (min). Once the user activates the Simulation button, an input file of GPSS/H is created by GEMISIMS as shown in Fig. 5. Next, GEMISIMS calls the executable of GPSS/H with path information about the input file to run simulations. The number of loads dumped per shift, utilization of the shovel and average number of trucks waiting at the shovel are extracted from the output file of GPSS/H. In particular, the number of loads dumped per shift is used to calculate the expected net profit per shift ($) using Equation 1.

$$NP = [N_L] \times P_L - C_F - (C_D + C_T) \times N_T \qquad (1)$$

Fig. 4. User interface of GEMISIMS to analyze optimal haulage routes of trucks using MLCPA (modified from Choi and Nieto, 2011).

Fig. 5. Example of an input file of GPSS/H (modified from Choi, 2011).

where NP is the net profit per shift ($), the solid brackets "[ ]" signify the Greatest Integer Function, N_L is the number of loads dumped per shift, P_L is the profit per load ($), C_F is the fixed cost for the mine (including the operating cost related to shovels) per shift ($), C_D is the wages per a truck driver per shift ($), C_T is the rental costs for each truck per shift ($) and N_T is the number of trucks allocated to the haulage route. By considering the utilization of the shovel, the average number of trucks waiting at the shovel and the expected net profit per shift, the user can determine the number of trucks required and the optimal dispatching intervals of trucks at each route.

GEMISIMS allows the user to create KML files which contain both spatial and temporal information related to the trucks' movements simulated through the haulage routes and to animate them using the time slider in the 3D render window. They use the TimeStamp element in KML that specifies the time as the dateTime format defined according to the Extensible Markup Language (XML) Schema standard (www.w3.org/TR/xmlschema-2/#isoformats) as follows:

$$yyyy\text{-}mm\text{-}ddThh{:}MM{:}sszzzzzz \qquad (2)$$

where $yyyy$ is a four-digit value of the year, mm is a two-digit value of the month, dd is a two-digit value of the day, T is the separator between the data and the time, hh is a two-digit value for hours (00-24), MM is a two-digit value for minutes (00-59), ss is a two-digit value for seconds (00-59) and $zzzzzz$ is either Z for a time specification that uses Coordinated Universal Time (UTC) or the time offset in relation to UTC in a format of $+hh{:}MM$ or $-hh{:}MM$.

The technique used for animating the movements of trucks is similarly applied in creating KML files to dynamically visualize and update the GPS tracking data of trucks. The details of how to manage the GPS tracking data using KML are described in Nieto et al. (2010). Once the user activates the button for tilted 3D view, GEMISIMS automatically zooms to a view directly over a 3D model of the truck that the GPS is taking. This functionality is based on the LookAt element in KML which can improve the user's understanding on spatial context.

Application

The Pasir open-pit coal mine is located in the east side of Kalimantan, Indonesia (115°53′E longitude and 1°51′S latitude). It has approximately a billion tons of recoverable reserves of bituminous coal and has been developed using large-scale open pit mining techniques since 1993 (Choi et al., 2006, Choi et al., 2008b; Choi et al., 2008a; Choi et al., 2009a; Choi et al., 2009b; Choi and Park, 2011). A region of the Roto North pit that covers 14.04 km² (3900 m × 3600 m) was selected as a study area (Fig. 6). The highest elevation is 188 m a.s.l., and the lowest is currently 102 m b.s.l.. Fig. 7 shows a haulage plan including the land-use map and
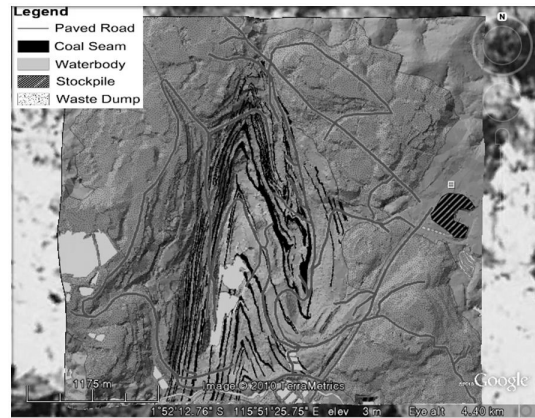

Fig. 6. Base map of the study area displayed in the embedded 3D render window of GE.
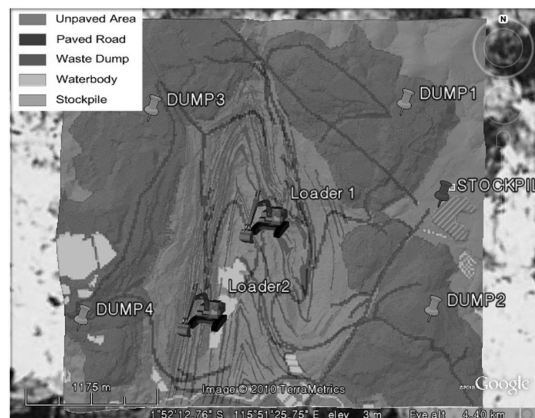

Fig. 7. Distributions of shovels, dumps and the ore stockpile for haulage operations in the study area.

distributions of shovels, dumps and a stockpile.

To analyze optimal haulage routes of trucks in the fixed dispatching system, we selected the option of round trip with the fixed assignment as a haulage type, the travel time as the objective function, KOMATSU HD785 as the truck model, the shovel 2 as an origin and the ore stockpile as a halfway point. Fig. 8 illustrates the optimal haulage routes determined by GEMISIMS. It estimated the travel time for the one cycle round trip as 12 min 27 sec. This estimation does not include the loading time of shovel 2 and the dumping time of trucks at the ore stockpile.

To determine the optimal number of trucks allocated to the route, GEMISIMS created an input file of GPSS/H according to the parameter settings in Fig. 8 and carried out simulations under different conditions of truck numbers

(3-8). Fig. 9 shows the simulation results. The net profit per shift can be maximized when six trucks are utilized for the haulage operation. In that case, the util ization of the shovel 2 is 97% and the average number of trucks waiting at the shovel 2 is 0.35. When six trucks are dispatched with an interval of 3 min, the trucks' movements can be simulated and animated in the 3D render window as shown in Fig. 10. Based on the animations, we can understand the behaviors of trucks during the haulage operation. For instance, in case of the truck 1, it uses the shovel 2 to load coal in Fig. 10A. Next, it moves uphill (Fig. 10B), and then arrives and dumps the coal at the ore stockpile (Fig. 10C). Empty truck 1 moves downhill to shovel 2 (Fig. 10D). GEMISIMS also allows the user to change the planer view into tilted 3D view over a 3D model of the truck (Fig. 11). This tilted 3D view is useful to trace a single truck's movement with understanding on spatial context.

In the application, GEMISIMS demonstrates the potential of GE as a tool for supporting open-pit mining operations. Although other GE-based software packages (Nieto et al., 2010; Sun et al., 2010a; Sun et al., 2010b; Choi and Nieto, 2011) have been developed in the mining industry, they cannot integrate the visualization capabilities of GE with mining simulation techniques. In contrast, GEMISIMS used the GPSS/H simulation language to perform the mining simulations. Therefore, it can

Fig. 8. Optimal haulage routes between the shovel 2 and the ore stockpile determined by GEMISIMS. Main user interface also shows the parameter settings to generate an input file of GPSS/H and conduct simulations of the open-pit truck haulage system consisting of the shovel 2, six KOMATSU HD785 trucks and the ore stockpile.

	1	2	3	4	5	6
Number of Trucks	3	4	5	6	7	8
Loads/Shift	71	94	116	135	140	140
Shovel Utilization(%)	51	68	84	97	100	100
Average Queue Length	0.02	0.05	0.12	0.35	1.14	2.14
Fixed Costs($)	250	250	250	250	250	250
Cost of Drivers($)	318	424	530	636	742	848
Cost of Trucks($)	675	900	1125	1350	1575	1800
Gross Profit/Shift($)	2105.15	2787.1	3439.4	4002.75	4151	4151
Net Profit($)	862.15	1213.1	1534.4	1766.75	1584	1253

Fig. 9. Simulation results provided by GEMISIMS to determine the optimal number of trucks allocated to the open-pit truck haulage system.
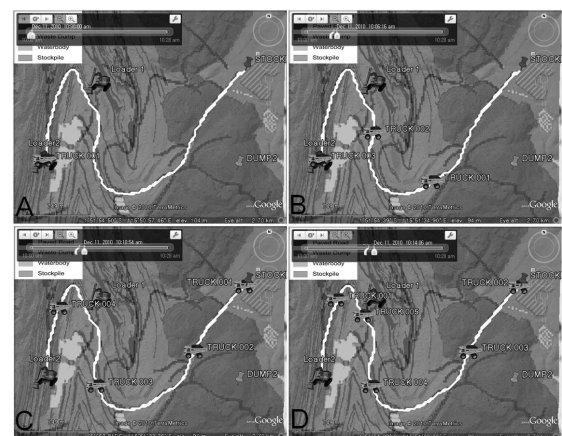

Fig. 10. Animations of the trucks' movements simulated by GEMISIMS for the haulage operation. (A) Dec 11, 2010-10:00:00 AM. (B) Dec 11, 2010-10:06:16 AM. (C) Dec 11, 2010-10:10:54 AM. (D) Dec 11, 2010-10:14:06 AM.
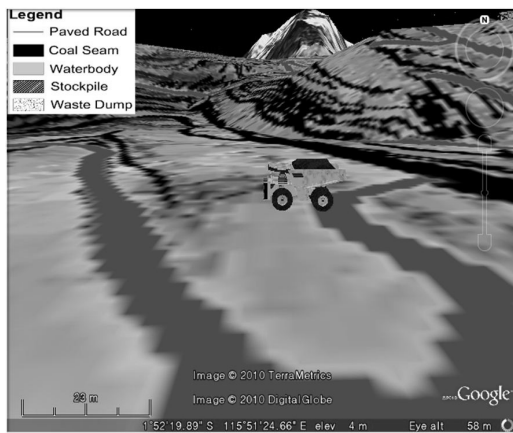
Fig. 11. Tilted 3D view of a truck model provided by GEMISIMS.

provide better information to understand open-pit truck/shovel haulage systems than other GE-based software packages.

Conclusions

We developed new software, GEMISIMS, to show the potential of GE as a simulating tool for an open-pit truck haulage system. GEMISIMS can analyze haulage routes of trucks between loading and dumping points using MLCPA and optimize the number of trucks which will be allocated to each route using the GPSS/H simulation language. When the number of trucks and their dispatching intervals are determined, GEMISIMS generates KML files that animate the movements of trucks during a haulage operation. Therefore, GEMISIMS can significantly improve the understanding of an open-pit truck/shovel haulage system. In addition, users can readily update the parameter settings related to the route optimization and mining simulations, GEMISIMS is most applicable to operating construction and mining sites, in various areas and countries, where the alteration of managerial decisions and economic conditions can dynamically change the demands for the optimal haulage routing with time.

GEMISIMS is not truly relevant as a fully automated haulage system at open-pit mining sites since the haulage operations in the changing outdoor environments are so difficult to fully automate and still require the hand of an experienced operator. However, this does not detract from the value of the technique described in this paper because it can support semi-automated operations, as an intermediate phase in the development of fully automated systems, by providing truck drivers and dispatchers with better information about the open-pit truck haulage system to improve the human operator's performance.

Although the simulation example presented in this paper is simple to consider more complex open-pit truck/shovel haulage systems with different types of trucks on the paths, the simulation capability can be easily extended by using the GPSS/H simulation language. In the future work, it would be desirable to include more sophisticated GPSS/H programs to extend the simulation functionality of GEMISIMS.

Acknowledgements

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