An expert system for hydraulic excavator and truck selection in surface mining

by C. Kirmanli* and S.G. Ercelebi*

Synopsis

The purpose of this paper is to develop an expert system for hydraulic excavator and truck selection in surface mining. Hydraulic excavators and trucks are finding increasing applications in mining operations. Hydraulic excavators are extensively used especially when bringing electricity to rural areas is difficult and for small-scale mining.

This paper describes an expert system, which selects the optimum hydraulic excavator truck configuration such that unit production cost is minimized and technical constraints such as geological, geotechnical and mining constraints are satisfied. The system has four modules: user interface, rules and an methods, databases and output module. The expert system in this study is developed within KappaPC shell. It supports object-orientated technology for the MS Windows environment.

The software provides a very useful tool to practitioners, saving time and cost. Equipment selection is a recurring and expensive problem of mine planning and often involves interdisciplinary experts from different fields. It is very difficult and expensive to bring together all these experts.

The capabilities of the expert system developed are illustrated in the paper. The software overcomes the difficulties of selecting the proper equipment for surface mining operations, which is very important, and results in substantial savings. Equipment databases for hydraulic excavators with 15-59 yd^3 capacities and trucks with 35-360 tons are constructed and these databases are used to select the proper configuration. A case study is carried out for Soma Surface Coal mines in Turkey.

Keywords: surface mining, expert systems, equipment selection, hydraulic excavators, diggability

Introduction

Surface mining is the most common method of mine production in the world. In surface mining, the required production is provided by various equipment groups, having different types and capacities. Choosing appropriate equipment is one of the most important factors for production system efficiency. Low-grade ore deposits have been increasingly mined because of exhausted high-grade ore deposits. Also, ore reserves which exist near the surface are mostly depleted. Because of the increase in cost, which is caused by increasing depths in surface mining, larger equipment capacities have been necessary. The huge amounts of material to be dug and hauled, especially in dispersed low grade ore deposit, have required bigger and heavier mining equipment.

In recent years, a hydraulic excavator and truck combination has been used in surface mining due to technological developments. This is mega sized equipment, which requires a great investment. For this reason, choosing the most suitable equipment is the most important factor. The wrong equipment selection causes low production efficiency and increases the unit cost. So, selecting proper equipment for surface mining must be carefully analysed and the optimum equipment configuration must be determined.

There are several techniques for surface mining equipment selection[1]. These techniques vary from classical methods to sophisticated computer techniques. Operation research techniques such as linear-integer programming, simulation and queuing theory have been widely used in early and recent applications. Artificial intelligence techniques, developed after the 1960s, are also found a place in the mining sector. Genetic algorithms, neural networks and expert systems are examples of commonly used artificial intelligence techniques.

In this study, an expert system is developed in order to select the optimum hydraulic excavator – truck combination. A combination, which realizes minimum unit production cost, is considered as optimum. Selected equipment also satisfies the geological, geotechnological and production constraints.

Expert systems in mining

The aim of artificial intelligence is to create machines that can perform complex tasks as well as, or better than humans. In order to

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perform these complex tasks, machines must be able to perceive reason, learn and communicate. Artificial intelligence applies human reasoning techniques to computers. An expert system is intended to act as a human expert who can be consulted on a range of problems that fall within his or her area of expertise[2].

Typically, the user of an expert system will enter into a dialogue in which he or she describes the problem (such as the symptoms of a fault) and the expert system offers advice, suggestions, or recommendations. The dialogue may be led by the expert system, so that the user responds to a series of questions or enters information into a spreadsheet. Alternatively, the expert system may allow the user to take the initiative in the consultation by allowing him or her to supply information without necessarily being asked for it.

Experts systems can be defined as a computer programs that rely on knowledge and reasoning to perform a difficult task usually performed only by a human expert. Operation research techniques and artificial intelligence techniques must be used for finding the optimum solution while, in mining applications, there is so much uncertainty and affecting parameters such as geological and technological parameters.

The inference engine and knowledge base are the main parts of an expert system. The explanation unit, user interface and knowledge acquisition system are other units. For creating the knowledge base, expert systems widely use three different types of approaches, which are production rules, frames and semantic networks. Production rules use if-then clauses and are commonly used in recently developed expert systems. A typical expert system is shown in Figure 1.[3,4]

Some examples of surface mining equipment selection expert systems are given briefly below.

Scoble *et al.*[5] developed a prototype knowledge based excavation equipment selection expert system that depends on geotechnical and equipment characteristics. It is developed by using Turbo Prolog. The system uses geotechnical parameters such as block size, rock strength and degree of weathering and also other mining related parameters such as production, excavation type, and equipment types, for generating rules.

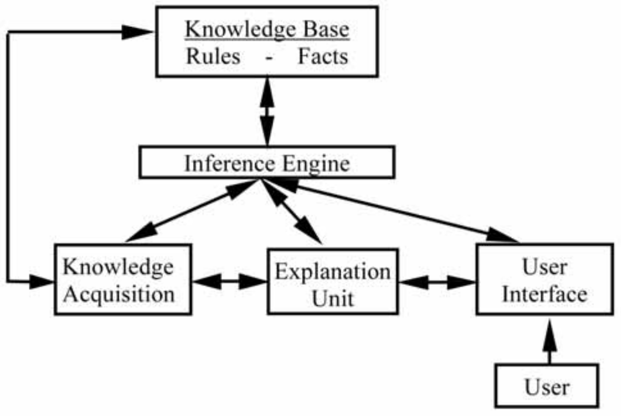


Figure 1—Typical expert system structure

Scraper is one of the oldest expert systems. It has been developed for scraper selection at the Université Laval on a LISP machine using KEE shell. KEE is a convenient shell for storing rules and databases into frame slots. Several different types scrapers' (i.e. single or twin-engine elevating scrapers, push-pull scrapers, etc.) performance curves and technical specifications are also structured into frames. Although parameters such as capital and operating costs, scraper performances, maintenance and spare part costs were not included in the prototype expert system, these components were added later to the database of the system and resulted in more satisfactory equipment selection.[6]

Erdem[7] developed an expert system for overburden removal equipment selection in surface coal mines. Haulage equipment was not taken into consideration for this expert system. A expert system having 85 parameters and 224 rules was developed by using PCPLUS shell to provide forward chaining method and frame slots. The knowledge and parameters are embedded into frames, which are called diggability, mining, topsoil, pit water, topography, highwall and spoil piles stability, economy, coal seams, equipment and overburden characteristics. Depending on the replies from consultation, a certainty factor is assigned to parameters, which is use to form rules in each frame. After completing the consultation, selected equipment is listed from the maximum to minimum of their cumulative certainty factor and during interrogation, some equipment, for example a dragline, is eliminated at the beginning of consultation.[8]

MINDER (MINe Design using Expert Reasoning) is another expert system used for selecting surface mining excavation and haulage equipment. The system was developed using the Xi Plus expert system shell running under MS-DOS. MINDER is capable of integrating commercial software such as Surpac, Datamine, AutoCAD, dBase IV and GPSS, and also programs written in Pascal are used to solve algorithmic problems and to make available integration with other software. Linguistic variables, certainty factors and fuzzy logic techniques are used for uncertainty and missing information. MINDER is able to link the SMMS (Strip-Mine Management System), a small knowledge-based system developed by the Advanced Computer Application Group to advise the end-user on the mine layout and design constraints.[9,10,11]

Dragline Selector is an expert system for dragline and stripping method selection in surface coal mines with flat-lying coal seams. The expert system was developed using XCON shell which uses a module hierarchy; these modules are the expert core module, stripping methods, dragline database and output module. Several dragline stripping methods are used in expert system and from the stripping methods module, the selected stripping method is determined by mathematical solution and range diagram analysis under the control of the expert core module. After selecting the dragline stripping method and convenient draglines for this method, the system calculates the cost of stripping for selected draglines. After the cost analysis, production simulations are carried out to determine the productivity of selected draglines. Finally, the dragline is determined to suit the stripping method and with the minimum cost.[12,13]

Ganguli and Bandopadhyay[14] developed the expert system for surface mining equipment selection by means of the Level 5 expert system shell. The expert system consists of four steps, which specify the purpose of the equipment selection and data entry, and assign relative importance (weight) to the factors and list of results. In the first step, the system selects the equipment by consulting the user. In the data entry step, factors such as flexibility and conditions of the selected task are given. In the next stage, the user specifies the relative importance of the factors for the mining condition by assigning numerical weights. Uncertainties called ratings, which the users can change depending on their expertise, of equipment are determined based on the condition of each factor and stored in database. These ratings are used to find the weighted value of the equipment.

An expert system for surface mining hydraulic excavator-truck selection

Mining engineering is interdisciplinary engineering and the mining engineer, has to take into consideration other interdisciplinary experts opinions in order to make a decision. But it is difficult to find experts from different disciplines whenever they are needed. For this reason, expert systems that are one of the widely used techniques of artificial intelligence are used to select the optimum hydraulic excavator and truck combination in surface mining.[15,16]

A hydraulic excavator and truck selection expert system is being developed within KappaPC shell. The chosen expert system shell, developed by IntelliCorp Company, supports object-orientated methodology for the Microsoft Windows platform. KappaPC provides some features such as object orientated programming, rule-based reasoning, rule sets, methods, session windows and images. Methods supported by KappaPC shell are like production rules. Avoiding long rule structures, reducing the number of rules and reducing the time between finding the target and starting a new search are important advantages of this method module. KappaPC's inference engine supports the rule-based knowledge base structure and forward and backward chaining methods for determining possible solutions. Another reason to select KappaPC as a shell is to be flexible enough to add or change the rules if necessary.

The hydraulic excavator and truck selection expert system developed has four modules: user interface, rules and methods, databases and output module. Rules are determined by 5 classes according to equipment selection criteria, which are diggability, material properties, equipment, operating factors and control rules. Figure 2 shows the system structure.

A user interface is common in all expert systems which makes it possible for the user to supply information by means of prepared questionnaires.

Production rules are constructed by using an IF-THEN format because the system supports the modular structure. New rules can be added to the system whenever needed. Some examples of production rules are given in the equipment selection criteria section.

Methods, formed with more than one rule, are widely used in expert systems to reduce production rules' complexity and working time. For example, 60 methods of excavator selection, 50 methods of truck selection and 25 methods of diggability are used in our system.

The expert system has two main databases, the hydraulic excavator database and truck database. In the truck database, there are 113 different types and models of trucks including detailed specifications. The excavator database consists of 85 front end and backhoe hydraulic excavators.

With the aid of the output module, the results are displayed on the screen and can either be printed or saved in a file.

Equipment selection criteria

For selecting of hydraulic excavators and trucks, equipment selection criteria must be determined. These criteria are collected in 6 different categories, which are:

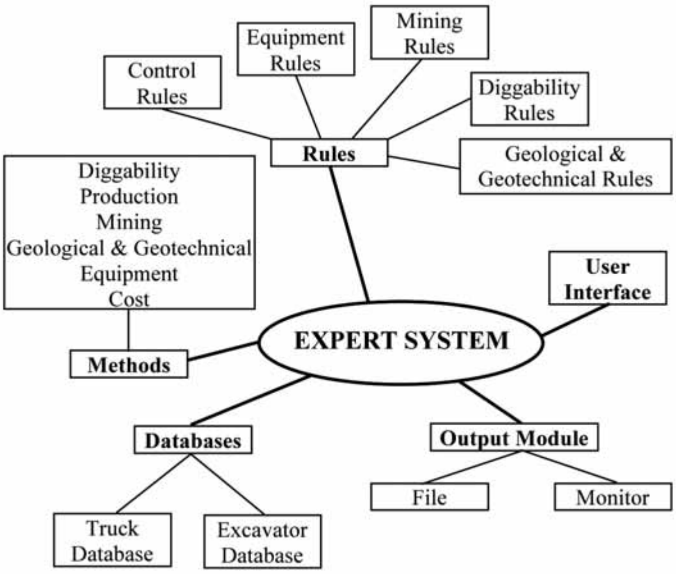


Figure 2—Hydraulic excavator–truck selection expert system structure

- Diggability
- Production criteria
- Mine parameters
- Geological and geotechnical factors
- Equipment criteria
- Unit production cost.

Diggability

Diggability can be defined as the ease with which the shovel digs a rock unit. There are several classification systems for assessing diggability, usually using the same large number of parameters. The main parameters of the diggability classification system are: uniaxial compressive strength, seismic velocity, weathering degree, the characteristics of joint sets and thickness of formation. Diggability classification systems developed by several researchers are described briefly below.

Franklin *et al.*[17] developed a classification system based on a graphical method, by using rock strength, discontinuity spacing and point load strength. A graph is divided into four areas and the areas are defined as digging, ripping, blasting for loosening and blasting for breaking.

Another classification system, which depends only on seismic velocity is given by Atkinson[18]; it categorizes equipment according to their digging performance. Seismic velocity is added as a parameter to the rippability classification by researchers Weaver[19], Sing *et al.*[20,21] and Pasamehmetoglu *et al.*[22] Smith[23] later modifies Weaver's classification by mainly neglecting the seismic velocity.

The ability of rock to be excavated, given by Rzhevsky[24], consists of two different categories: the first is for soft, compact and weathered rocks and the second is for broken and blasted rocks.

The 'diggability index' rating method was devised by Muftuoglu[25]. This index, which is derived by the summation of the rated values of input parameters, considers both geotechnical factors and excavating equipment capabilities. Muftuoglu and Scoble[26] define five rock classes based on four geotechnical parameters, uniaxial compressive strength, bedding spacing, joint spacing and weathering.

An empirical ground classification system based on rock strength, block size, weathering and relative ground structure was developed by Hadjigeorgiou and Scoble[27]. Geotechnical parameters are rated and combined to suggest an 'excavation index', which is related to excavation effort and excavation classes.

Karpuz[28] proposed an excavation rating system utilizing five rock mass and rock material properties relevant to the excavation method and excavator performance: uniaxial compressive strength, rock hardness, discontinuity spacing, degree of weathering and seismic wave velocity. The proposed rating system helps in the selection of excavation equipment as well as drilling and blasting requirements.

Basarir and Karpuz[29] have devised a rippability classification system for marl stones in lignite mines. Rock parameters included in the system are uniaxial compressive strength, seismic wave velocity, discontinuity spacing and Schmidt hammer hardness. Each of these input parameters is rated separately, and rippability classes of rocks are determined according to the final rating. Accordingly, appropriate dozer types and their expected production rates are specified.

Based on Rzhevsky, Muftuoglu and Pasamehmetoglu diggability classification systems, a new diggability classification has been developed for the hydraulic excavator-truck selection expert system. In the new diggability classification, digging conditions are classified as easy, medium, medium-hard, hard and very hard. In this new classification system, the proposed diggability grade is determined from parameters such as uniaxial comprensive strength, weathering degree, seismic velocity, average discontinuity spacing and bedding thickness, as shown in Table I and Table II.

Parameters in Table I consist of 5 different digging classes and their ranges have been assigned to all these grades. For example, if uniaxial comprensive strength is 90 MPa, the sub-grade is taken as 20. This process is performed for all parameters, and after these operations, the total diggilability grade is calculated by accumulating all sub grades. As seen in Table II, the digging class has been classified from easy to very hard, depending on the total diggability grade.

Production criteria

Annual production, total reserve, working days per year and working hours per day, stripping ratio and, annual amount of overburden are given as examples of production criteria. The annual overburden amount is calculated from the annual production and stripping ratio. From the required ore production and waste removal, the life of mine is calculated and its relation to the operating life of the equipment is also determined.

Table I

Proposed diggability criteria for expert system

Parameters	Digging class				
	1	2	3	4	5
Uniaxial comp. strength (MPa)	<20	20–40	40–60	60–100	>100
Grade	0	10	15	20	25
Weathering degree	Decomposed	Highly weathered	Moderately weathered	Slightly weathered	Unweathered
Grade	0	5	10	15	20
Seismic velocity, (m/sn)	<1750	1750–2000	2000–2500	2500–3200	>3200
Grade	5	12	20	28	30
Average discontinuity spacing (m)	<0.1	0.1–0.5	0.5–1	1–1.5	>1.5
Grade	5	10	15	20	25
Bedding thickness (m)	<0.1	0.1–0.3	0.3–0.6	0.6–1.5	>1.5
Grade	0	5	10	20	30

Table II

Diggability Classification used in the expert system

Digging class	Total diggability grade	Hydraulic excavator
Easy	<20	Easy digging, no blasting required
Medium	20–40	Easy digging, no blasting required
Medium-hard	40–70	Blasting required
Hard	70–100	Blasting required
Very hard	>100	Blasting required

Mine parameters

Bench height, bench width, weather conditions, underground water, haul distance (waste and mineral), ground conditions, job efficiency factor are some examples of mine parameters.

Geological and geotechnical factors

Type of formation, mineral density, waste density, bedding thickness, uniaxial compressive strength, swelling factor, elasticity modulus, blasting condition and average size distribution after blasting are examples of geological and geotechnical factors.

Equipment criteria

Bucket capacity, vehicle weight, payload, digging height, ground pressure, power, bucket cycle times, speed, bucket fill factor, operating life, truck struck or heaped body capacity, etc. can be given as examples of equipment criteria.

Unit production cost

The cost estimation analysis of the selected excavators and their assigned trucks, having different capacities and numbers, are carried out to find the minimum production cost for the optimum hydraulic excavator and truck combination. Unit costs of fuel, oil, tyre and labor must be supplied by the user for the cost analysis.

A tyre hourly cost is calculated assuming between 1 000–6 000 hours for mining trucks and 500–7 000 hours for articulated trucks. When tyre life is in question, TKPH ratings and manufacturer recommendations are considered. Hourly fuel and oil costs are calculated separately for each truck and excavator. In order to calculate the fuel and lubrication costs of each piece of equipment, manuals and performance handbooks are utilized (Caterpillar Performance Handbook[30], Liebherr Technical Handbook[31]).

Labour, tyre, fuel and lubrication costs are used to determine the equipment operating costs. Amortization is calculated on the basis of the capital cost of the equipment. The economic life of excavators and trucks is taken from manufacturer handbooks and included in the database.

Expert system architecture

The structure of the expert system is illustrated in Figure 3. As shown in Figure 3, the interrogation of the diggability criteria is the first phase of the expert system. Then, production, mine parameters and geotechnical parameters are taken from the user by means of the interrogation section of the expert system.

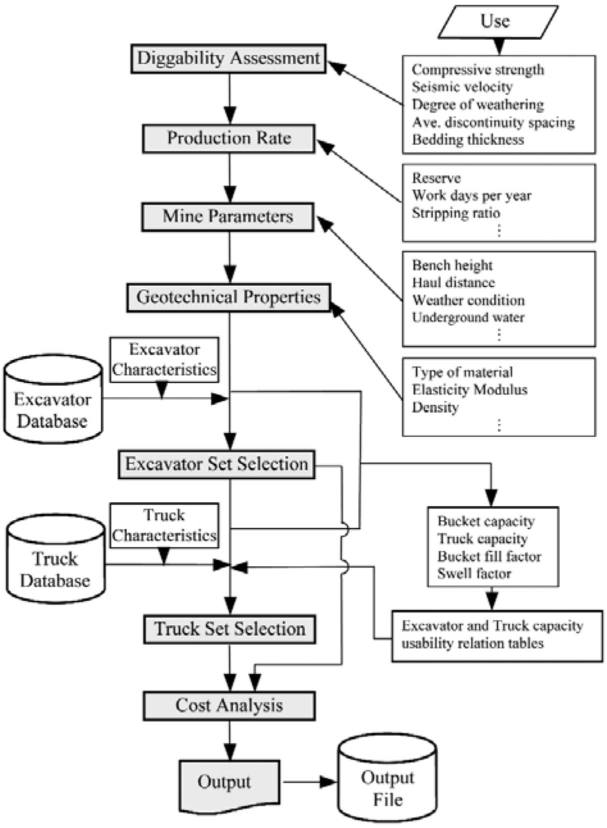


Figure 3—Expert system architecture

The expert system starts with the screen shown in Figure 4. After starting the system, the diggability screen is displayed, as shown in Figure 5. In order to determine diggability, uniaxial comprensive strength, weathering degree, seismic velocity, average discontinuity spacing and bedding thickness values are supplied to the expert system from the diggability assessment input screen. Material and coal density data are also given in this screen.

Diggability criteria are determined according to information supplied. Table I is used to determine the total diggability grade, then Table II is used to find the diggability class.

An example of the rules, constituted by an 'IF-THEN' structure, in order to determine diggability class is given in Figure 6.

If seismic velocity is unknown, the user is asked for the elasticity modulus and Poisson ratio and the seismic velocity is calculated by using these values and compressive strength.

Production and mine parameter information is given to the expert system on the mining section screen (Figure 7). In mining section, some information related to mine parameters, such as company name, reserve and annual production amount, bench height, etc. are required by the expert system for excavator and truck selection calculations and to run related production rules.

After production information is supplied, the expert system determines the mine life and annual required waste production, using the stripping ratio.

The next step in interrogation is that the geotechnical criteria are given to the expert system from the material section screen shown in Figure 8. In this section, blasting conditions for the waste and mineral and average size distribution of blasted material are also supplied by the user. The elasticity modulus and Poisson ratio values, which are assigned to -99 as default values, are not used when the seismic velocity is given at the beginning of interrogation.

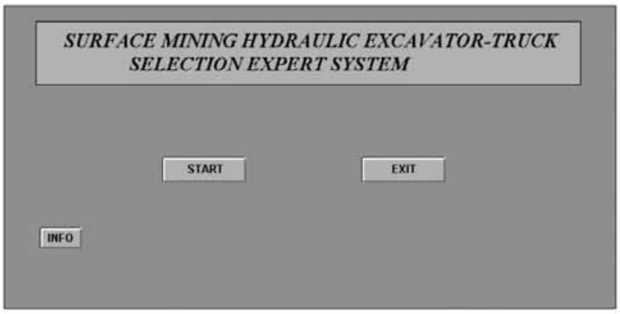
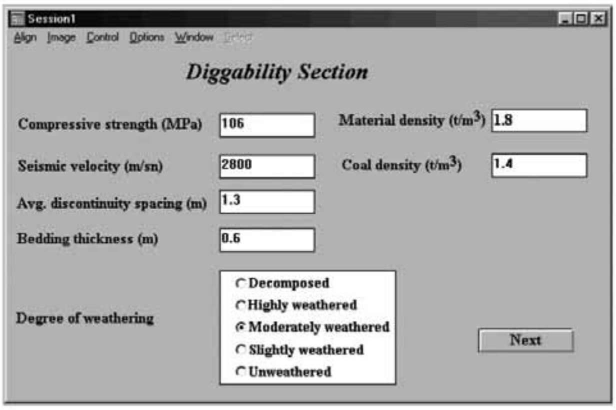


Figure 4—Expert system start screen



Compressive strength (MPa) 106

Seismic velocity (m/sn) 2800

Avg. discontinuity spacing (m) 1.3

Bedding thickness (m) 0.6

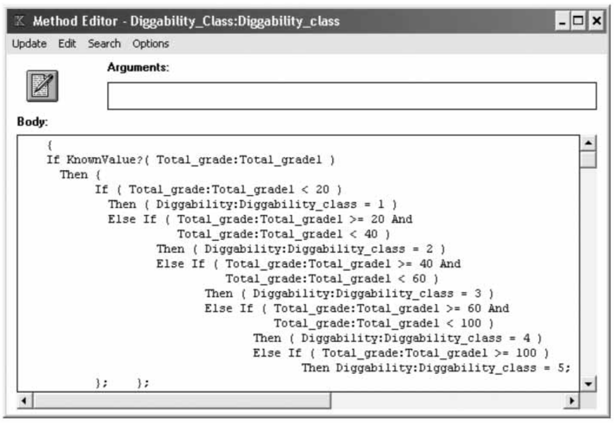
Material density (t/m^3) 1.8

Coal density (t/m^3) 1.4

Degree of weathering

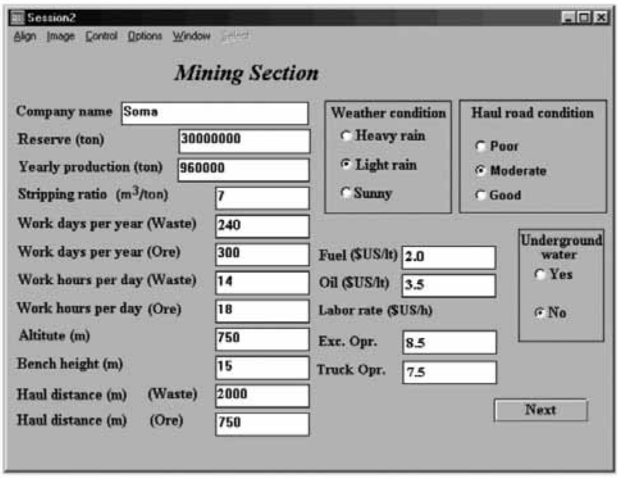
○ Decomposed
○ Highly weathered
● Moderately weathered
○ Slightly weathered
○ Unweathered

Figure 5—Diggability assessment input screen



```
    {
    If KnownValue?( Total_grade:Total_gradel )
      Then {
           If ( Total_grade:Total_gradel < 20 )
             Then ( Diggability:Diggability_class = 1 )
             Else If ( Total_grade:Total_gradel >= 20 And
                       Total_grade:Total_gradel < 40 )
                   Then ( Diggability:Diggability_class = 2 )
                   Else If ( Total_grade:Total_gradel >= 40 And
                             Total_grade:Total_gradel < 60 )
                         Then ( Diggability:Diggability_class = 3 )
                         Else If ( Total_grade:Total_gradel >= 60 And
                                   Total_grade:Total_gradel < 100 )
                               Then ( Diggability:Diggability_class = 4 )
                               Else If ( Total_grade:Total_gradel >= 100 )
                                     Then Diggability:Diggability_class = 5;
           };    };
```

Figure 6—An example of a digging production rule



Company name Soma

Reserve (ton) 30000000

Yearly production (ton) 960000

Stripping ratio (m^3/ton) 7

Work days per year (Waste) 240

Work days per year (Ore) 300

Work hours per day (Waste) 14

Work hours per day (Ore) 18

Altitute (m) 750

Bench height (m) 15

Haul distance (m) (Waste) 2000

Haul distance (m) (Ore) 750

Weather condition: ○ Heavy rain ● Light rain ○ Sunny

Haul road condition: ○ Poor ● Moderate ○ Good

Underground water: ○ Yes ● No

Fuel ($US/lt) 2.0

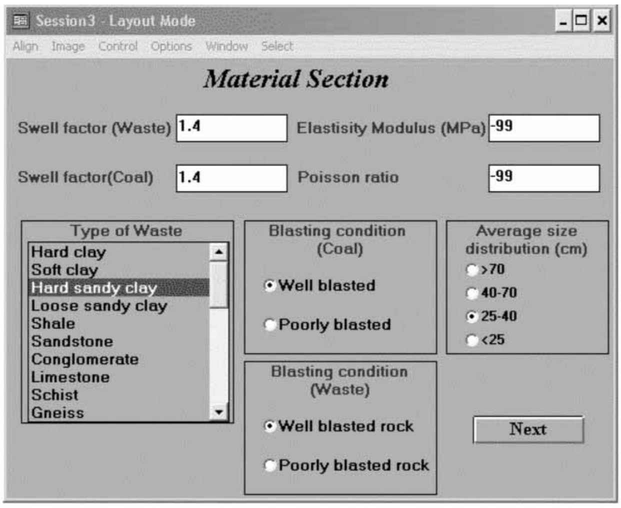
Oil ($US/lt) 3.5

Labor rate ($US/h)

Exc. Opr. 8.5

Truck Opr. 7.5

Figure 7—Mining interrogation section screen



Swell factor (Waste) 1.4

Swell factor(Coal) 1.4

Elastisity Modulus (MPa) -99

Poisson ratio -99

Type of Waste: Hard clay, Soft clay, **Hard sandy clay**, Loose sandy clay, Shale, Sandstone, Conglomerate, Limestone, Schist, Gneiss

Blasting condition (Coal): ● Well blasted ○ Poorly blasted

Average size distribution (cm): ○ >70 ○ 40-70 ● 25-40 ○ <25

Blasting condition (Waste): ● Well blasted rock ○ Poorly blasted rock

Figure 8—Material properties interrogation section screen

Blasting size distribution must be supplied by the user. The bucket fill factor depends on the size distribution of the blasted material.

Excavator selection

After the interrogation screens, hydraulic excavator selection is made by the expert system. At first, the excavator bucket capacity, which depends on the amount of waste material to be excavated, must be determined by means of assigning values to formulas given in Equation [1]. In order to determine the excavator bucket capacity, the daily amount of overburden to be removed is calculated from the annual production of the mineral and annual working days.

$$q = \frac{V}{T} \qquad [1]$$

where:

q : Daily amount of waste (m^3/day)
V : Annual amount of waste (m^3/year)
T : Working days per year (days/year)

In order to convert excavator capacity to excavator bucket capacity, the daily excavator working hours and number of cycles must be determined.

$$C = \frac{S * i * 3600}{p} \qquad [2]$$

where:

C : Daily number of excavator cycles
S : Work hours per day (h/day)
i : Job efficiency (%)
p : Cycle time (s)

Excavator bucket capacity is calculated from the total amount of waste determined by means of the stripping ratio. After that, the bucket capacity is calculated for the different number of excavators, which can achieve the daily amount of waste. For example: for 1 excavator for all of the waste, for 2 excavators half of the daily amount of waste, for 3 excavators one-third of the daily amount of waste, and so on. The maximum excavator number is assumed to be 10 in the expert system.

After determination of the daily number of excavation cycles, the amount of waste in one cycle is calculated depending on the amount of waste. Therefore, excavator numbers and their bucket capacities are determined in accordance with the daily amount of waste. Nowadays, the biggest hydraulic excavator capacity is 59 yd^3 (45 m^3). For this reason, excavators with a bucket capacity which is over 59 yd^3 are not taken into consideration.

After determining the bucket capacity, the excavator is examined for the pressure it applies to the ground. Ground bearing capacity is a determining factor here in selecting or eliminating some excavators. Also weather conditions and the existence of underground water affects the ground bearing capacity. Bearing capacities of many ground structures are included in the system database.

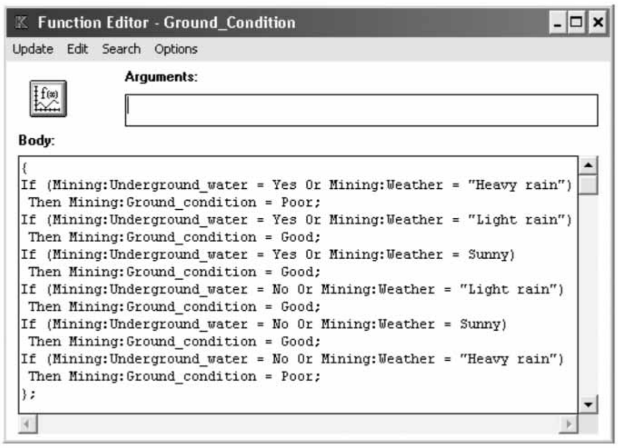
If the ground bearing capacity is higher than the pressure applied by an excavator but the floor condition is poor, then a smaller excavator is selected. In Figure 9, an example of the ground condition rule, which is developed to determine the ground condition using underground water and weather conditions, is shown.

The next step is the reach factor of excavators. Depending on the mine bench height entered, the excavator is examined based on its reach factor. If the selected excavator's reach factor is not appropriate, then this excavator is eliminated from the optimal list.

Truck selection

Once an excavator is selected, the proper truck capacity is determined in accordance with the relationship between bucket capacity and truck capacity. This relationship is developed and reassessed for trucks between 35 and 360 tons and excavators for different capacities. The usability area is determined for the trucks, which are filled with 3 to 6 passes of the excavators (Figure 10). The line that passes through the middle reflects the ideal line.

In order to select the correct trucks for an excavator, with a bucket capacity determined earlier, the difference between the volume filled by the excavator with 3 to 6 passes and the remaining empty or overloaded volumes is examined. Despite trucks with optimum passes being allocated for an excavator, an empty volume may remain in the body of the trucks. The remaining empty volumes of trucks must be minimal in order for the production loss to be minimal. Also overloaded volume should not be more than 10% of the truck capacity. A truck with a minimum empty capacity is assumed to be the most appropriate one by the expert system. Excavator-truck capacity relations depending on the numbers of excavator bucket passes, is constructed and given in Table III.



```
{
If (Mining:Underground_water = Yes Or Mining:Weather = "Heavy rain")
 Then Mining:Ground_condition = Poor;
If (Mining:Underground_water = Yes Or Mining:Weather = "Light rain")
 Then Mining:Ground_condition = Good;
If (Mining:Underground_water = Yes Or Mining:Weather = Sunny)
 Then Mining:Ground_condition = Good;
If (Mining:Underground_water = No Or Mining:Weather = "Light rain")
 Then Mining:Ground_condition = Good;
If (Mining:Underground_water = No Or Mining:Weather = Sunny)
 Then Mining:Ground_condition = Good;
If (Mining:Underground_water = No Or Mining:Weather = "Heavy rain")
 Then Mining:Ground_condition = Poor;
};
```

Figure 9—An example of a ground condition rule

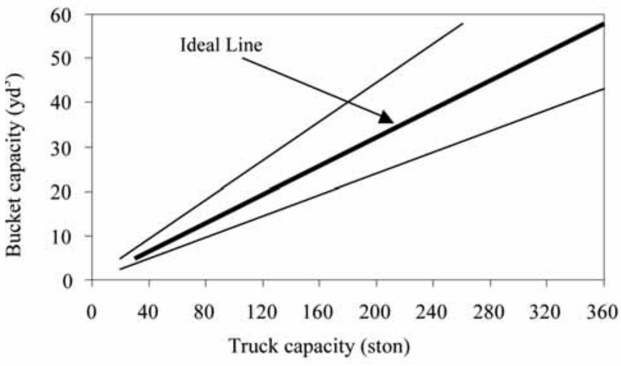


Figure 10—Optimum excavator bucket capacity and truck capacity

After 3 to 6 passes of the excavator, the remaining empty or overloaded volumes are shown as bold in Table IV. Different tables are formed in accordance with the bucket fill factor ranging from 0.75 to 1.0, taken in steps of 0.05 and a swelling factor ranging from 1.0 to 1.5, taken in steps of 0.05. From these tables, truck capacities having minimum remaining empty volumes and overloaded volumes are determined. Average truck haul speeds are used as given in manufacturers' catalogues in order to determine the haul and return times. Loading times are calculated according to the number of bucket loads and excavator cycle times.

In Table III and Table IV, excavators between 59 yd^3 (45 m^3) and 15 yd^3 (11.5 m^3), and trucks between 360 and 35 ton are given. Trucks, whose capacities are lower, then excavator bucket capacity and trucks that can be loaded with fewer than 3 and more than 6 buckets are left blank in Table III and Table IV.

In Table IV empty volumes are shown as (-) and overloaded volumes are shown as (+).

A truck with more horsepower is preferred if the capacity is the same but the model is different. Powerful trucks perform more efficiently while climbing grades and when the engine is first started. Thus, a truck with a greater HP/ton rate and with a greater horsepower engine is preferred.

The rules, which are constructed according to the relationship between excavator capacity – truck capacity – remaining empty and overloaded volume tables, are embedded into expert systems.

To here, the optimal set of excavator-truck fleets is selected, satisfying mining, production, geological and geotechnical constraints. The last step is to select the optimum combination, which has the lowest total unit cost of production, among feasible sets. The costs are determined for each capacity of excavators and truck fleet. Amortization and maintenance costs, fuel and lubrication consumption are taken from databases. The user is asked to supply fuel, oil and labour costs.

Table III

Excavator capacity—truck capacity usability relation example (Bucket fill factor = 0.85, swell factor = 1.4)

Truck capacity		**Excavator capacity yd^3 (m^3)**									
(ton)	**(m^3)**	**59 (45.1)**	**46 (35.1)**	**44 (33.6)**	**40 (30.6)**	**38 (29)**	**34 (26)**	**30 (23)**	**25 (19.1)**	**18 (13.8)**	**15 (11.5)**
360	221	5	6	6							
320	175	4	5	5	5	6	6				
260	132	3	3	4	4	4	5	5	6		
240	129	3	3	4	4	4	5	5	6		
215	115	3	3	3	3	4	4	5	6		
195	105		3	3	3	3	4	4	5		
190	103		3	3	3	3	4	4	5		
170	102		3	3	3	3	4	4	5		
150	78						3	3	4	5	6
120	64							3	3	4	5
100	60								3	4	5
85	46									3	4
75	40										3
65	36										
40	23										
35	21										

Table IV

Relationship between excavator capacity—truck capacity – remaining empty truck and overloaded volume (m^3) (Bucket fill factor = 0.85, swell factor = 1.4)

Truck Capacity		**Excavator capacity yd^3 (m^3)**									
(ton)	**(m^3)**	**59 (45.1)**	**46 (35.1)**	**44 (33.6)**	**40 (30.6)**	**38 (29)**	**34 (26)**	**30 (23)**	**25 (19.1)**	**18 (13.8)**	**15 (11.5)**
360	221	+4,5	-10,4	-19,4							
320	175	+5,4	+0,5	-7,0	-22,0	-1,0	-19,0				
260	132	+3,3	-26,7	+2,4	-9,6	-16,0	-2,0	-17,0	-17,4		
240	129	+6,3	-23,7	+5,4	-6,6	-13,0	+1,0	-14,0	-14,4		
215	115	+20,3	-9,7	-14,2	-23,2	+1,0	-11,0	-0,0	-0,4		
195	105		+0,3	-4,2	-13,2	-18,0	-1,0	-13,0	-9,5		
190	103		+2,3	-2,2	-11,2	-16,0	+1,0	-11,0	-7,5		
170	102		+3,3	-1,2	-10,2	-15,0	+2,0	-10,0	-6,5		
150	78						-0,0	-9,0	-1,6	-9,0	-9,0
120	64							+5,0	-6,7	-8,8	-6,5
100	60								-2,7	-4,8	-2,5
85	46									-4,6	-0,0
75	40										-5,5
65	36										
40	23										
35	21										

Case study

The case study was carried out for waste removal at Soma Surface Coal Mines operated by Turkish Coal Enterprise. The interrogation screens and the data for the mine are given in Figures 5, 7 and 9.

The diggability grade of this field is calculated as 95 according to the diggability class given in Table I according to the parameters shown in the input screen (Figure 5). The diggability class is determined as ‘hard’ according to Table II and requires blasting.

After blasting, waste material is in the condition of well blasted. The average blasted size distribution is 25–40 cm and the bucket fill factor is 0.85 as a result. A partial example of the rules to find the fill factor depending on the material type and blasting condition, is given in Figure 11.

The next step is to determine the excavator bucket capacity. Assuming the required daily waste is removed by 1,2,3,…,10 excavators, appropriate bucket capacities are determined. Second criterion is to examine excavator weights and pressure applied to the ground. Ground bearing capacity is the determining factor to eliminate or select some excavators. For example, a 25 yd^3 excavator applies 0.19 MPa pressure to the ground and the mine ground bearing capacity is 0.23 MPa. Excavators, whose bucket capacities are 40–59 yd^3 apply and ground pressure of more than 0.23 MPa are eliminated. After eliminating 40–59 yd^3 excavators, the remaining excavators with bucket capacities of 15–38 yd^3 are candidate excavators.

Candidate excavators selected by the system are examined next, if their reach is 15 m or higher, which is the bench height for the mine. According to the reach height, a second elimination is carried out.

Average haul and return times depend on the dump site distance. The manoeuvre time of the trucks near the excavator is taken as approximately 30 seconds. Manoeuvre and dump times at the dump point are taken as between 70 and 90 seconds, depending on the truck capacity.

In the next step, the hourly number of cycles of the trucks depending on truck cycle times, are determined. The amount of waste hauled for each truck is calculated and the required number of trucks is calculated.

The formulas used for cycle times and unit cost are given below.

$$T_{truck} = t_1 + t_2 + t_3 + t_4 \qquad [3]$$

$$N_{cycle-truck} = \frac{3600 \times i}{T_{truck}} \qquad [4]$$

$$P_{truck} = \frac{N_{cycle-truck} \times v \times N_{bucket}}{k} \qquad [5]$$

$$P_{fleet-truck} = P_{truck} \times N_{truck} \qquad [6]$$

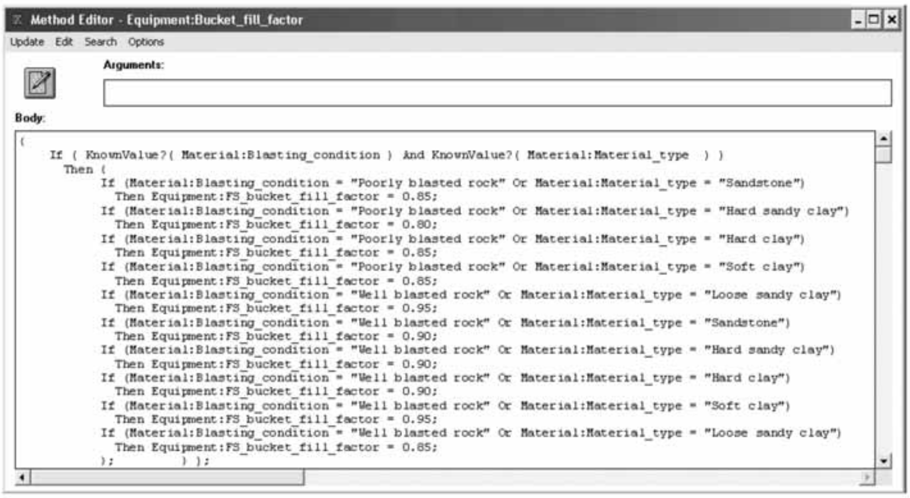
$$c = \frac{C_{eks} + C_{fleet-truck}}{P_{fleet-truck}} \qquad [7]$$

where:

P_{truck} : Production rate of truck
$P_{fleet-truck}$: Production rate of truck fleet
T_{truck} : Total cycle of truck
t_1 : Truck haul time
t_2 : Truck return time
t_3 : Truck load time
t_4 : Truck manoeuvre and dump time
N_{truck} : Number of trucks
$N_{cycle-truck}$: Number of cycle of truck
i : Job efficiency
v : Excavator bucket capacity
N_{bucket} : Number of buckets
k : Swell factor
C_{eks} : Total excavator cost
$C_{fleet-truck}$: Total truck fleet cost
c : Unit production cost ($US/m^3)

For the case study, production rate is 960 000 t/year and the stripping ratio is 7 m^3/ton. The annual waste to be removed is found to be 6 720 000 m^3/year.

The range of the excavator bucket capacities considered is 15–59 yd^3 and the hourly production of these excavators is calculated for the example mine. Bucket cycle times are found



```
(
    If ( KnownValue?( Material:Blasting_condition ) And KnownValue?( Material:Material_type  ) )
      Then (
           If (Material:Blasting_condition = "Poorly blasted rock" Or Material:Material_type = "Sandstone")
             Then Equipment:FS_bucket_fill_factor = 0.85;
           If (Material:Blasting_condition = "Poorly blasted rock" Or Material:Material_type = "Hard sandy clay")
             Then Equipment:FS_bucket_fill_factor = 0.80;
           If (Material:Blasting_condition = "Poorly blasted rock" Or Material:Material_type = "Hard clay")
             Then Equipment:FS_bucket_fill_factor = 0.85;
           If (Material:Blasting_condition = "Poorly blasted rock" Or Material:Material_type = "Soft clay")
             Then Equipment:FS_bucket_fill_factor = 0.85;
           If (Material:Blasting_condition = "Well blasted rock" Or Material:Material_type = "Loose sandy clay")
             Then Equipment:FS_bucket_fill_factor = 0.95;
           If (Material:Blasting_condition = "Well blasted rock" Or Material:Material_type = "Sandstone")
             Then Equipment:FS_bucket_fill_factor = 0.90;
           If (Material:Blasting_condition = "Well blasted rock" Or Material:Material_type = "Hard sandy clay")
             Then Equipment:FS_bucket_fill_factor = 0.90;
           If (Material:Blasting_condition = "Well blasted rock" Or Material:Material_type = "Hard clay")
             Then Equipment:FS_bucket_fill_factor = 0.90;
           If (Material:Blasting_condition = "Well blasted rock" Or Material:Material_type = "Soft clay")
             Then Equipment:FS_bucket_fill_factor = 0.95;
           If (Material:Blasting_condition = "Well blasted rock" Or Material:Material_type = "Loose sandy clay")
             Then Equipment:FS_bucket_fill_factor = 0.85;
           );          ) );
```

Figure 11—Partial example of rules for the bucket fill factor

Table V

Excavator productions

	Excavator capacity yd^3 (m^3)									
	59 (45.1)	46 (35.1)	44 (33.6)	40 (30.6)	38 (29)	34 (26)	30 (23)	25 (19.1)	18 (13.8)	15 (11.5)
Waste production per excavator (m^3/h)	1636	1355	1355	1291	1253	1179	1098	936	736	632
Required excavator #	1	2	2	2	2	2	2	2	3	3
Total waste production (m^3/year)	6185429	10242419	10240474	9759920	9469826	8914698	8301136	7079864	8349966	7169163
Overproduction (%)		52	52	45	41	33	24	5	24	7

by using bucket fill factors and swelling factors supplied by the user. For example, hourly production of a 25 yd^3 excavator is:

$$V = \frac{v \times 0.764 \times 3600 \times \eta \times i}{p \times k} = \frac{25 \times 0.764 \times 3600 \times 0.85 \times 0.83}{37 \times 1.4} = 936.49\ m^3/h$$

V : Hourly excavator bucket capacity (m^3/h)
v : Excavator bucket capacity (yd^3)
η : Bucket fill factor
i : Efficiency factor
p : Bucket cycle (sec)
k : Swell factor

The next step is the truck selection. Depending on the bucket capacity, trucks, which will be filled by 3–6 passes, are suitable trucks. The number of trucks to be assigned to each excavator, assuming no dispatching is found by using the classical approach.

Table V shows the production achieved for excavators. Excavators producing more than 20% of the annual requirement are eliminated for this example. The overproduction per cent can be supplied by the user if desired.

After selecting the feasible set of excavator and truck fleets, the last step is to select the optimum configuration, which has the lowest total unit cost. The costs are determined for each excavator-truck fleet. Fuel and lubrication consumption, amortization and maintenance costs are taken from the databases. Excavator and truck hourly cost examples are given in Table VI and Table VII respectively.

The unit production costs ($US/$m^3$) for the hydraulic excavator-truck combination determined by the expert system are given in Table VIII. The combination of three 15 yd^3 excavators with eighteen 100 ton trucks and 3 spare trucks provides the minimum unit production cost of 0.87 $US/$m^3$.

The expert system suggests the combination, which has the minimum cost, as optimum. The other two alternatives are listed as Alternative 2 and Alternative 3 (Figure 12). The second alternative is two 25 yd^3 excavators with ten 170 ton trucks and 2 spare trucks. For the second alternative the cost is 0.95 $US/$m^3$. The third alternative is three 15 yd^3 excavators with twenty-one 85 ston trucks and 4 spare trucks resulting in a 0.96 $US/$m^3$ unit production cost. Optimum equipment properties are given in Figure 13.

Conclusion

An expert system for hydraulic excavator and truck selection for surface mining has been developed. The hydraulic excavator–truck combination is increasingly being used in surface mining because of technological developments and because electrical energy is not being needed. The system has equipment databases obtained from manufactures, and mine specific data are entered into the system by means of interrogation screens.

Table VI

Excavator hourly cost ($US/h)

Eks. capacity		Capital cost	Operating cost	Total cost
yd^3	m^3			
59	45	93.75	668.91	762.66
46	35.1	75.00	595.46	670.46
44	33.6	71.25	572.50	643.75
40	30.6	68.75	529.41	598.16
38	29	66.25	486.57	552.82
34	26	62.50	463.61	526.11
30	23	53.75	416.89	470.64
25	19	48.75	320.60	369.35
18	13.8	92.50	234.92	327.42
15	11.5	87.50	192.54	280.04

Table VII

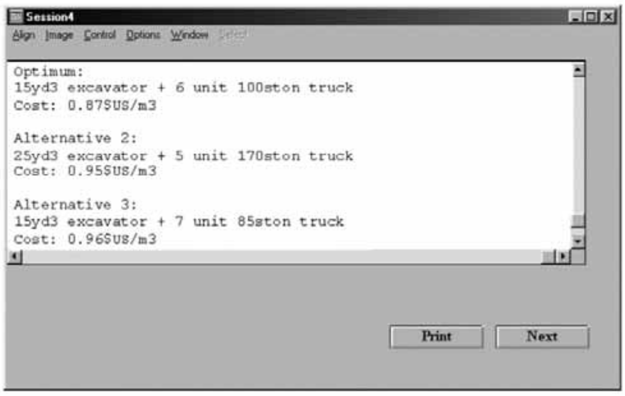
Truck hourly cost ($US/h)

Truck Capacity (ton)	Capital cost	Operating cost	Total cost
360	63.00	329.27	392.27
320	50.00	285.88	335.88
260	38.00	236.29	274.29
240	35.20	207.35	242.55
215	33.00	199.86	232.86
195	31.00	171.07	202.07
190	30.60	170.75	201.35
170	27.00	160.38	187.38
150	46.67	167.08	213.75
120	31.25	148.70	179.95
100	22.50	117.14	139.64
85	29.17	116.77	145.94
75	25.00	101.73	126.73
65	15.27	90.71	105.97
40	13.83	71.49	85.33
35	12.00	62.95	74.95

Table VIII

Excavator—truck unit production costs ($US/m^3)

Truck capacity		Excavator capacity yd^3 (m^3)									
(ton)	(m^3)	59 (45)	46 (35)	44 (33.6)	40 (30.6)	38 (29)	34 (26)	30 (23)	25 (19.1)	18 (13.8)	15 (11.5)
360	221	1.66	1.22	1.20							
320	175	1.70	1.11	1.10	1.24	1.11	1.16				
260	132	1.64	1.20	1.08	1.10	1.10	1.03	1.18	1.13		
240	129	1.50	1.12	1.01	1.03	1.02	0.96	1.09	1.04		
215	115	1.46	1.10	1.08	1.18	1.00	1.04	1.06	1.02		
195	105		1.02	1.00	1.09	1.09	0.96	1.07	1.04		
190	103		1.02	1.00	1.09	1.08	0.96	1.07	1.04		
170	102		0.95	0.93	0.94	0.93	0.89	0.91	0.95		
150	78						1.04	1.07	1.05	0.92	1.00
120	64							1.03	1.10	0.97	0.97
100	60								0.97	0.97	0.87
85	46									1.02	0.96
75	40										0.99
65	36										
40	23										
35	21										

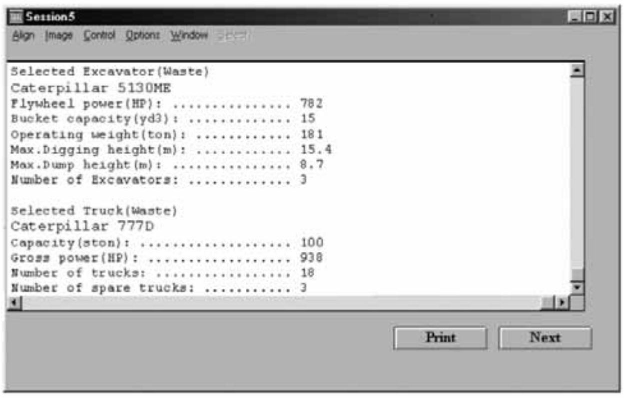


```
Optimum:
15yd3 excavator + 6 unit 100ston truck
Cost: 0.87$US/m3

Alternative 2:
25yd3 excavator + 5 unit 170ston truck
Cost: 0.95$US/m3

Alternative 3:
15yd3 excavator + 7 unit 85ston truck
Cost: 0.96$US/m3
```

Figure 12—Equipment alternatives screen



```
Selected Excavator(Waste)
Caterpillar 5130ME
Flywheel power(HP): ............... 782
Bucket capacity(yd3): ............. 15
Operating weight(ton): ............ 181
Max.Digging height(m): ............ 15.4
Max.Dump height(m): ............... 8.7
Number of Excavators: ............. 3

Selected Truck(Waste)
Caterpillar 777D
Capacity(ston): ................... 100
Gross power(HP): .................. 938
Number of trucks: ................. 18
Number of spare trucks: ........... 3
```

Figure 13—Selected optimum equipment properties

The diggability classification system developed is one of the criteria to select excavation equipment. Mine parameters and geological and geotechnical parameters are other criteria used to select equipment.

Truck selection is carried out by choosing the most appropriate trucks for the excavator selected such as remaining empty and overloaded volume in truck body is minimum after 3–6 excavator bucket passes.

After selecting feasible sets of excavator-truck fleets, the optimum excavator-truck combination is selected by minimizing the unit production cost. In addition, 2 other alternatives are supplied to the user for comparison. A case study is demonstrated for Soma Surface Coal Mine in Turkey. Three units of 15 yd^3 hydraulic excavators along with 18 units of 100 ton trucks has been found as the optimum solution. This solution provides 0.87 $US/m^3 as the minimum unit production cost.

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