Production, Cost, and Environmental Impact of Loading Equipment in Surface Coal Mining in Appalachia

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ABSTRACT

This paper presents the results of research related to development of a software tool for the determination of the production, cost, and environmental impact of loading equipment in surface coal mining in Appalachia. Loading equipment includes rope shovels, front hydraulic shovels, backhoe shovels, and front-end wheel loaders. The design and procedures used in this research include three interrelated modules for each type of loading equipment: (i) production, (ii) ownership and operating costs, and (iii) environmental impact of loading operations. The latter includes particulate matter (PM_{10}), total suspended particulate matter (TSP), carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), sulfur oxides (SO_x), volatile organic compounds (VOCs), and sound pressure level. This research is a part of a broader industrial project related to the development of software systems for the selection of productive, cost-efficient, and eco-friendly mining systems.

INTRODUCTION

Geologic formations in the Appalachian region consist of overburden and coal seams of varying thicknesses interspersed between multiple layers of interburden. Overburden and interburden must be removed before the coal is extracted. Basic surface mining unit operations include drilling, blasting, loading, hauling, and dumping. Loading equipment includes rope shovels, hydraulic front shovels, backhoe shovels, and front-end wheel loaders. The main goal in the selection of loading equipment is to maximize production rate while minimizing overall cost and environmental impact.

Surface coal mining in the Appalachian region presents many environmental challenges. Major environmental disturbances in loading operations are air pollutants and sound exposure. Air pollutants include particulate matter (PM_{10}), total suspended particulate matter (TSP), carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), sulfur oxides (SO_x) and volatile organic compounds (VOCs). The mining industry is compelled by public pressure and stringent governmental regulations to reduce its environmental impact. Future surface coal mining operation will need to substantially decrease environmental disturbances during overburden removal and coal extraction to achieve "low impact" mining by incorporating new practices and design features.

To date, different approaches and software packages have been developed to determine the production and cost of loading equipment in surface mining. The Fleet Production and Cost Analysis Program (FPC) is a software package developed by Caterpillar that assists in predicting fleet productivity and associated costs within given operational conditions. FPC is a very useful tool for comparing the various types of loader-truck systems based on production and cost parameters. A similar software package, the Haulage Analysis Tool (HAT), was developed by Komatsu. The

TALPAC, by Runge, is another software package commonly used by mining engineers to estimate loader and truck requirements, productivity, and overall costs for surface mining operations. This software uses the stochastic Monte Carlo method to simulate loading and hauling operation over a specific haul profile. It also provides sensitivity analysis over a wide range of production factors. However, all of these software tools lack any consideration of the environmental impact of loading and hauling equipment.

A number of studies have been conducted to analyze emissions from mining and construction equipment. Lewis et al. (2009) described governmental regulations that limit emission of air pollutants, identified construction equipment emission sources, and compared their data with data obtained from other sources. Sharrard et al. (2007) conducted research on the environmental and energy implications in the construction industry and concluded that equipment fuel consumption is almost twice the level indicated in various governmental reports; and therefore, that the impact of air emission is 30% greater for particulate matter and almost twice the levels for NO_x and VOCs. Kean et al. (2000) conducted a study to determine emissions of NO_x and PM_{10} for off-road diesel equipment based on diesel fuel consumption. Gautam et al. (2002) used an in-field testing method to determine emission factors for diesel powered off-road engines, including excavators, front-end loaders, dozers, and street sweepers. Bogunovic and Kecojevic (2009) conducted research to determine surface mining equipment CO_2 emissions. Lewis (2009) estimated fuel consumption, exhaust, and dust emissions of excavators, track loaders, wheel loaders, backhoes, dozers, off-road trucks, and motor graders. Frey et al. (2010) used a portable emission monitoring system to gather data from excavators, backhoes, dozers, track type loaders, wheel loaders, graders, generators and off-road trucks. Dallmann and Harley (2010) conducted research to determine exhaust emissions for NO_x and fine particulate matter ($PM_{2.5}$) from mobile sources using a fuel-based methodology. Kecojevic and Komljenovic (2010) determined the quantity of CO_2 emitted by haul trucks and associated costs that may arise from potential CO_2 legislation.

Organiscak and Reed (2004) described the average and instantaneous peak dust levels 100 feet from haul roads. The authors also published the results of research related to the evaluation of safe following distance for equipment in order to avoid overexposure to respirable dust from lead trucks (Reed and Organiscak 2005).

Overexposure to sound is an important health hazard. According to Kovalchik et al. (2009), many health hazards associated with mining operations have improved, with the exception of hearing loss. Excessive sound levels are detrimental to mine workers. Bolt, Baranek, and Newman, Inc. (1971) established empirically-based relationships of heavy equipment sound exposure as a function of horsepower. In 1982, the Federal Highway Administration (FHWA) (Bowlby and Cohn 1982) published a standardized construction sound model called Highway Construction Noise Model (HICNOM). More recently, a number of models have been developed for the prediction of sound exposure in construction projects, such as CadnaA, SoundPLAN, and the Environmental Noise Model (FHWA 2006). In these models, equipment sound data is expressed as a sound pressure level at a reference distance.

The objective of the present study was to develop a software tool that can be used for the assessment of production, cost, and environmental impact of various loading equipment in surface coal mining in the Appalachian region. This research is a portion of a broader project on development of a software system for the selection of productive, cost-effective, and eco-friendly mining systems, a project that is sponsored by the Appalachian Research Initiatives for Environmental Sciences (ARIES). The text that follows provides a description of the methodology used in this research, results, and concluding remarks.

METHODOLOGY

To achieve the objectives of this research, three interrelated modules were developed in the

Microsoft Visual Studio.NET programming environment. Module I determines production parameters, specifically hourly and annual production rates. Module II considers different components of ownership and operating costs associated with loading equipment, and determines total operating costs in dollars per hour, dollars per year, and dollars per cubic yard. Module III determines the environmental impact of loading equipment, including dust and exhaust emissions and sound pressure level. Emissions are presented in pounds per hour, pounds per year, and pounds per cubic yard.

Various sources and equations given by Caterpillar (2010), Komatsu (2009), Hartman (1992), Kennedy (1990), InfoMine (2010), Runge (1998), and P&H Mine Pro (2003) are used and incorporated into Modules I and II in order to determine production rates and cost.

Several estimation methods can be used to determine the exhaust emissions of mining equipment. These methods include: direct measurement or sampling, mass balance, fuel analysis, and emission factors (NPI 2008). Direct measurement uses continuous emission monitoring or sampling data from the working area. In the mass balance method, the difference between amount of a specific substance in output and input of the system is used to calculate the emission of a specific pollutant. The fuel analysis method is based on chemical or physical properties of substance (e.g., ideal gas law) and the application of a set of mathematical relationships.

The emission factors method is commonly used for determination of exhaust emissions. This method is based on multiplication of the activity rate (in units of weight, volume, distance, or duration per unit of time) by the appropriate emission factors. These factors are expressed as the emission rate when a unit of equipment is operated in an average manner. Emission factors are usually mass-based and stated in units of mass per unit of fuel consumed, mass per unit of activity (e.g., pound per horsepower hour), or mass per mile traveled. The latter method is applied to Module III of this study.

Exhaust emission of loading equipment (CO, NO_x, SO_x, VOC, and CO_2) is determined as follows:

$$E_i = EF_i \times HFC \times H \tag{1}$$

where E_i is annual emission of the substance i (lb/year), EF_i is emission factor of substance i (lb/gallon), HFC is hourly diesel fuel consumption (gallon/hr), and H is the number of operating hours per year (hr/year). Values of emission factors are adopted from NPI (2002) and EPA (1985).

Dust emission is categorized according to the size range of the component particles: TSP and PM_{10}. The TSP is the mass loading of airborne particles determined gravimetrically by a high volume air sampler. The PM_{10} refers to the mass loading of airborne particles that pass through a size selective inlet with a 50% efficiency cut-off at 10 μm aerodynamic diameter (NPI, 1999). In other words, TSP is the total of all particles suspended in the air from loading operation. The PM_{10} refers to the subset of TSP, including particles smaller than 10 μm in diameter. In this study, dust emission is determined as follows:

$$E_i = A \times EF_i \times (1 - CE_i/100) \tag{2}$$

where E_i is emission rate of pollutant i (lb/year), A is production rate (tons/year), EF_i is uncontrolled emission factor of pollutant i (lb/ton), CE_i is overall control efficiency of pollutant i (%), and TSP and PM_{10} are pollutants i.

According to the Australian National Pollution Inventory Agency (NPI 2012), dust emission factors for loading equipment working on overburden material can be determined as follows:

$$EF_i = K_i \times 0.0035 \times \frac{\left(\frac{U}{7.22}\right)^{1.3}}{\left(\frac{M}{2}\right)^{1.4}} \tag{3}$$

where U is mean wind speed (ft/sec), and M is moisture content (% by weight). The factor K_i for TSP and PM_{10} is equal to 0.74 and 0.35, respectively.

The TSP emission factor for digging and loading equipment working on coal extraction can be determined as follows:

$$EF_{TSP} = \frac{1.28}{M^{1.2}} \tag{4}$$

The PM_{10} emission factor is determined as follows:

$$EF_{PM_{10}} = \frac{0.0985}{M^{0.9}} \tag{5}$$

In the absence of on-site specific data on wind speed and moisture content, the default values for emission factors derived from NPI (2012) can be used. Based on this reference, TSP and PM_{10} emission factors for loading operation in overburden material are 0.0125 and 0.006, and for coal extraction, these factors are 0.0145 and 0.007 lb/ton, respectively.

The sound pressure level is the level of sound at a measuring point. Therefore, the sound produced by equipment should be described by specifying the measurement distance along with sound pressure level. Sound pressure level (L_p) can be expressed as follows (Mollenhauer and Tschoeke 2010):

$$L_p = 20 \times \log\left(\frac{p}{P_0}\right) \tag{6}$$

where p is sound pressure (Pa), and P_0 is the reference sound pressure ($P_0 = 2 \times 10^{-5}$ Pa).

An alternative way to describe sound produced by a machine is the sound power level (L_w):

$$L_w = 10 \times \log\left(\frac{W}{W_0}\right) \tag{7}$$

where W is sound power emitted by the source (watts) and W_0 is reference sound power level ($W_0 = 10^{-12}$ watts).

Therefore, the relation between sound pressure level and sound power level can be written as follows:

$$L_w = L_p + 10 \times \log\left(\frac{A}{A_0}\right) \tag{8}$$

where A_o is reference surface which is 1 square meter and A represents the area of measuring surface, which is determined as follows:

$$A = 2\pi \times r^2 \tag{9}$$

where r is distance from the sound source.

Both sound power level and sound pressure level are defined on a logarithmic scale, called the decibel (dB). Decibels are a useful way of handling very small or very large scalar values, defined as follows:

$$dB = 10 \times \log_{10}\left(\frac{\text{Quantity measured}}{\text{Reference level}}\right) \tag{10}$$

It should be noted that decibels defined for sound power and sound pressure level are completely different, because reference level for sound pressure level is $P_0 = 2\times10^{-5}$ Pa, while reference level for sound power level is $W_0 = 10^{-12}$ watts. It is a means for comparing two sounds, which can be defined by comparing the sound level with a reference sound.

Based on a report by the British Standards Institution (BSI, 2009), the permissible sound power level of shovels is calculated as follows:

$$L_w = \begin{cases} 103 & P \le 55\text{ kW } (\le 73.76\text{ hp}) \\ 84 + 11 \times \log P & P > 55\text{ kW } (> 73.76\text{ hp}) \end{cases} \tag{11}$$

and for front-end wheel loader:

$$L_w = \begin{cases} 101 & P \le 55\text{ kW } (\le 73.76\text{ hp}) \\ 82 + 11 \times \log P & P > 55\text{ kW } (> 73.76\text{ hp}) \end{cases} \tag{12}$$

where P is engine power.

Therefore, the sound pressure limit measuring at 50 ft from shovel will be:

$$L_p = \begin{cases} 71.36 & P \le 55\text{ kW } (\le 73.76\text{ hp}) \\ 52.36 + 11 \times \log P & P > 55\text{ kW } (> 73.76\text{ hp}) \end{cases} \tag{13}$$

And, for front-end wheel loader:

$$L_p = \begin{cases} 69.36 & P \leq 55\text{ kW } (\leq 73.76\text{ hp}) \\ 50.36 + 11 \times \log P & P > 55\text{ kW } (> 73.76\text{ hp}) \end{cases} \quad (14)$$

It should be noted that exact value of sound pressure level for mining equipment should be determined by on-site measurements since its level varies widely (FHWA 2006). Values presented in above equations only represent maximum level of allowed sound pressure for different equipment based on the BSI (2009).

RESULTS

Production, cost, and environmental modules developed for the hydraulic front shovel are shown in Figure 1.

In the production module, it is necessary to input values for the following factors: bucket volume; engine power; fill factor; material density; shovel cycle time; availability; operating efficiency; number of operating hours per year in order to determine volume of the material in the bucket; bucket payload; and hourly and annual production rates.

The cost module requires input values for these parameters: purchase cost; ownership period; depreciation rate; interest, insurance and tax rates; cost per gallon of fuel; operator rate; and maintenance factor. The following parameters are calculated: residual value; value to be recovered through work; capital cost; interest, insurance and tax costs; total ownership cost per hour and year; maintenance, wear parts, and labor cost; fuel cost; total operating cost per hour and year; and the total cost in dollars per cubic yard, hour and year. It should be noted that two options are available for the determination of fuel consumption. The first one allows determination of fuel consumption based upon on-site site measurements, while the second option calculates the fuel consumption based upon specific engine load factor.

The environmental module requires input values for these factors: emission factors of pollutants as follows: total suspended particular matter, airborne particles, sulfur oxides, nitrogen oxides, carbon monoxide, volatile organic compounds, and overall control efficiency factors. Output values in pounds per hour, year, and cubic yard include PM_{10}, TSP, CO_2, CO, NO_x, SO_x and VOCs. The sound pressure value is given in dB(A).

Figures 2 and 3 show production, cost, and environmental modules developed for the backhoe shovel and front-end wheel loader, respectively. The same procedure described for the hydraulic front shovel is applied to the backhoe shovel and front-end wheel loader. However, the latter requires inclusion of the cost of tires.

Figure 4 shows production, cost, and environmental modules developed for the rope shovel. The production module is the same as the one used for hydraulic shovel. Cost module includes the cost of electricity rather than diesel fuel, while environmental impact includes only PM_{10}, TSP, and sound pressure value.

The next phase of the research should include: (i) field measurements of environmental parameters, (ii) calibration, validation and sensitivity analysis of the model, (iii) development of the software help function and a User's Manual, and (iv) training for mining personnel regarding usage and data manipulation within software application.

CONCLUSION

The objective of this study was to develop a software tool for the assessment of production, cost, and environmental impact of various loading equipment in surface coal mining in the Appalachian region. Three interrelated modules (production, cost, and environmental impact) were developed in the Microsoft Visual Studio. NET programming environment. The research presented here may be used by mining professionals to help determine hourly and annual production rates, ownership, and operating costs associated with loading equipment, and environmental impact related to loading equipment such as dust and exhaust emissions and sound pressure level.

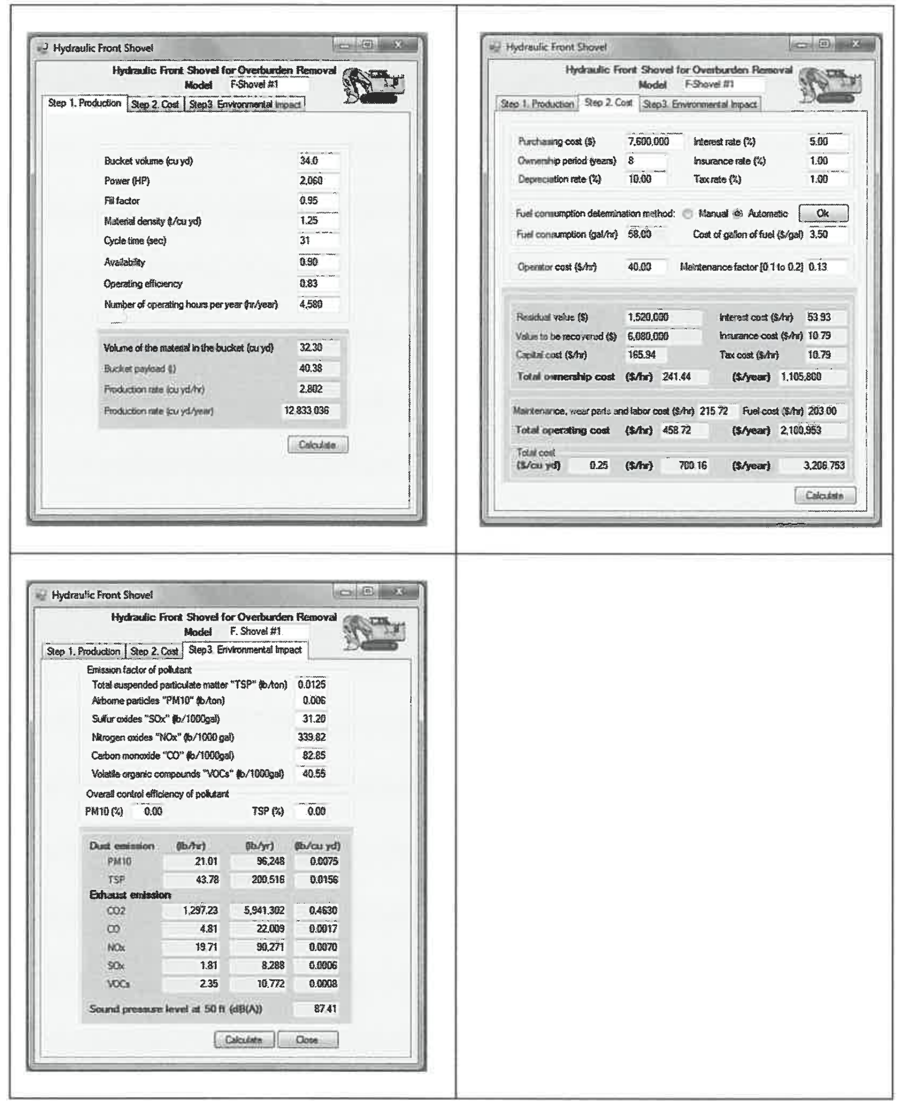

Figure 1. Production, cost, and environmental impact modules for hydraulic front shovel

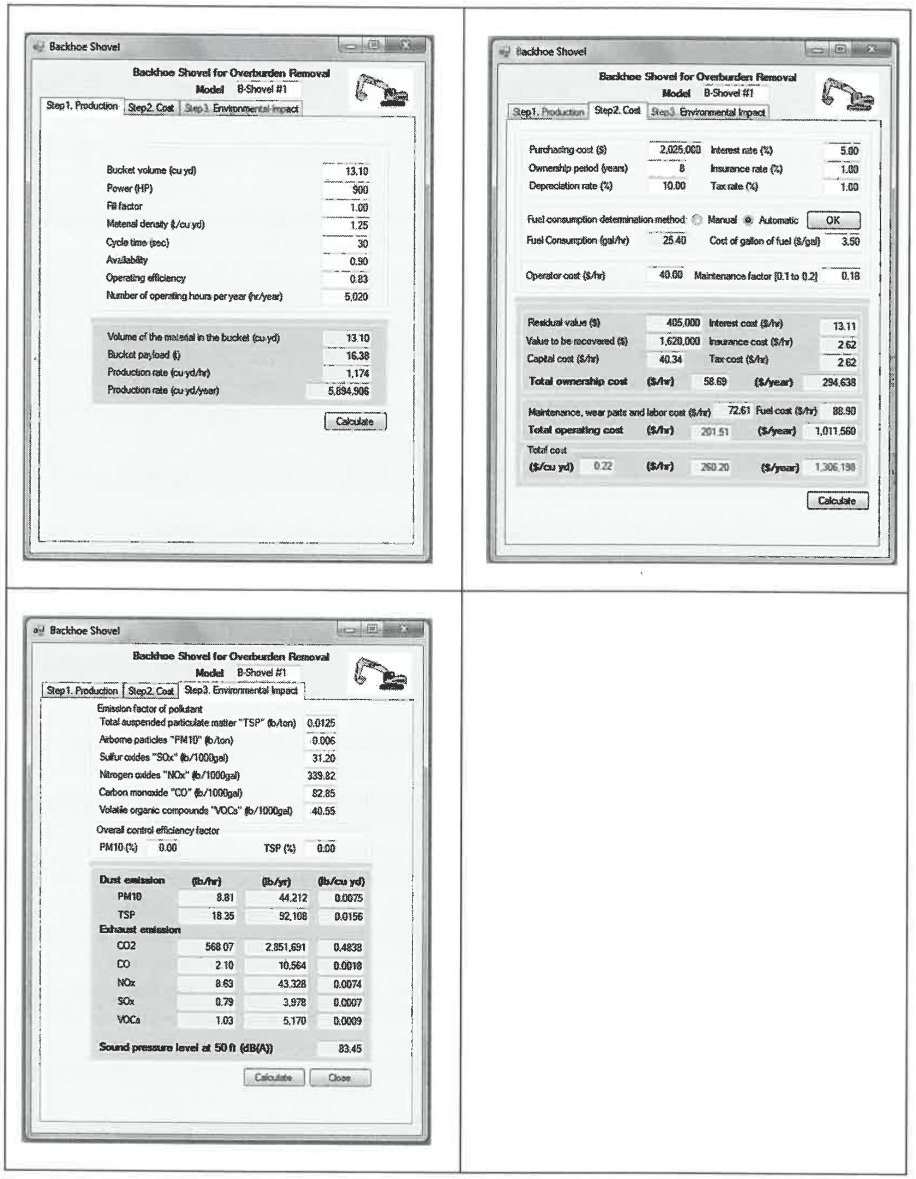

Figure 2. Production, cost, and environmental impact modules for backhoe shovel

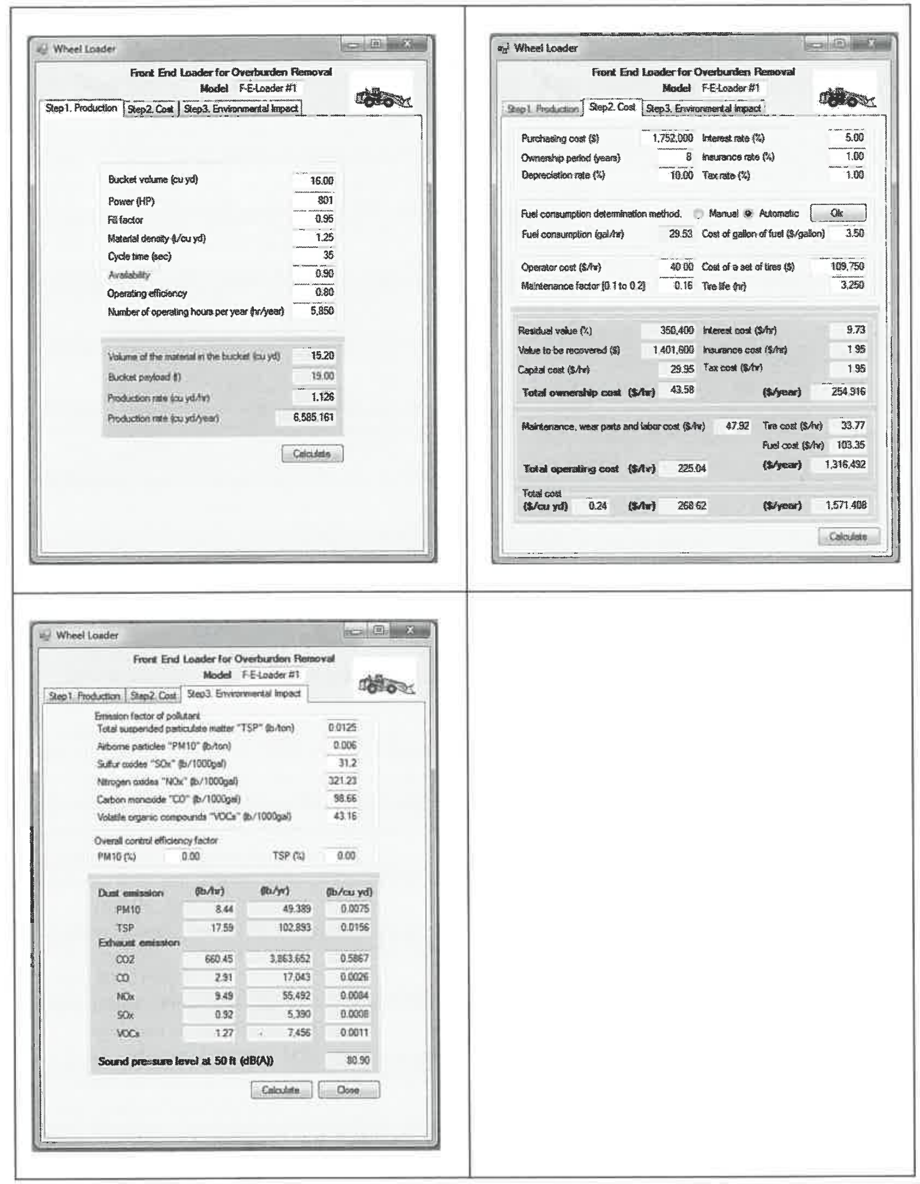

Figure 3. Production, cost, and environmental impact modules for front-end wheel loader

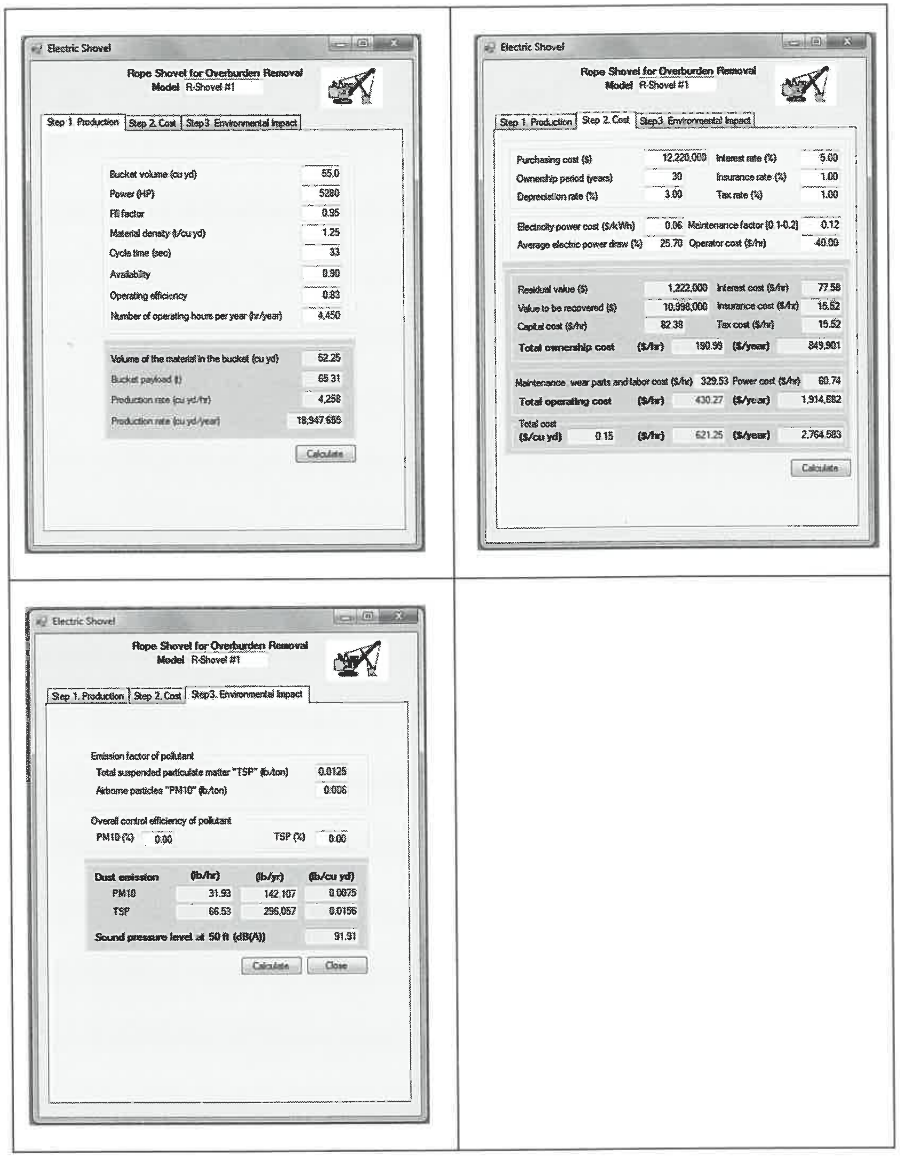

Figure 4. Production, cost, and environmental impact modules for cable (electric) shovel

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