

MACHINERY SELECTION FOR DEMOLITION AND RECYCLING OF PAVEMENTS: A SIMULATION-BASED TOOL

Hassan Nasir*, Rashid Rehan,** Rizwan Younis,*** Fazal Mabood,**** Salman Saeed,**
Muhammad Sagheer Aslam**

ABSTRACT

Proper selection of the type and number of machinery on construction is critical to the total cost and duration of projects. This especially applies to projects involving using of heavy machinery such as earthmoving projects. Currently, many construction managers – especially in Pakistan, rely on their intuition and judgement based on past experience to select their construction machinery fleet configuration. This approach is obviously subjective and prone to inefficient utilization of resources. Computer-based tools, such as simulation models, have the potential to greatly benefit the construction managers in their routine tasks. This paper presents a unique simulation tool based on the system dynamics methodology to help the construction manager in investigating the cost and duration implications of various combinations of machinery items. Utility of the developed model is illustrated with the help of a case study involving demolition and recycling of a flexible pavement.

KEYWORDS: Machinery selection, heavy construction equipment, system dynamics, cost efficiency, project duration.

INTRODUCTION

Pavement and road construction main heavy machinery plays a big role, time and cost has significant implications. Equipment selection is a critical factor when trying to complete a project within budget and on schedule. For any kind of work item, the manager has available several types of different equipment for same job. Production rates, consumption, rental charges and their number in a project are variables. Hence, various compositions of machinery fleet can be employed on a project, each with different implications for cost and duration of the project. The selection of equipment type and number is usually (and in Pakistan, almost always) is carried out by construction managers based on their past experience and intuition. This subjective approach can be easily seen as not being cost effective and efficient in terms of project completion times. The situation is especially exacerbated when the construction manager does not have sufficient past experience dealing with any kind of available machinery, or does not account for the randomness inherent in the variables listed above. Thus, there is a strong need of a decision aiding tool that helps the construction manager in this particular task. Accordingly, various researchers have attempted to address this need by developing a variety of computational tools. A few of these are briefly discussed below.

Moselhi and Alshibani¹ present crew optimization

module required within planning, tracking, and control of earthmoving operations. Assisted by spatial technologies such as global positioning system and geographic information system, their developed model employs genetic algorithm to find near optimum crew

A computer-based program based on hybrid knowledge-base system and genetic algorithms was developed by Haidar et al.² to select equipment and optimize excavation and haulage operations. This decision support system was specific in application to the opencast mining industry. Denby and Schofield³ developed expert system for selection of excavation and haulage equipment in mining. Equipment ranking is performed using relational operations and fuzzy logic techniques.

Amirkhanian and Baker⁴ present a rule-based expert system for selection of earth-moving equipment in construction projects. The developed system comprised of a main knowledge base and one module each for small, medium, large and extra-large projects. A wide range of equipment is included in the knowledge base but some parameters such as the length of the workday (8hr/day) are not amenable to changes.

Marzouk and Moselhi⁵ utilized genetic algorithms to optimize costs of earthmoving operations by identifying the type and number of equipment in various fleet configurations.

* Department of Civil Engineering, King Abdulaziz University, Jeddah, Saudi Arabia.

** National Institute of Urban Infrastructure Planning, University of Engineering & Technology, Peshawar-Pakistan.

*** Center of Advancement of Trenchless Technologies, University of Waterloo, Canada.

**** Pavement Design & Evaluation officer, Ministry of Transportation, Ontario, Canada.

A more comprehensive model is the one presented by Zhang⁶ that combines multiple attribute utility theory and a statistical approach to optimize equipment configurations for earthmoving operations.

In all of the works cited above, the one by Zhang⁶ is by far the most useful approach in that it eliminates the need for an exhaustive search of all possible simulation replications and further adopts a methodology that reduces the computational time. However, notwithstanding the usefulness of its capabilities, it is observed that the Zhang⁶ model is not amenable to an easy understanding and modification by the common industry professional. In this paper, therefore, a user-friendly simulation tool based on the system dynamics methodology is presented. The presented model does not automatically identify the most optimum fleet configuration and instead relies on the user carrying out a number of iterations. But this limitation may be seen as strength in that during the course of simulation iterations, the user gains a better understanding of the interrelationships and trade-offs involved in various equipment characteristics and numbers. In locations, such as Pakistan, where the construction manager has limited choices for the type and number of equipment available, the number of possible combinations (and hence simulation iterations) reduces anyway. Hence, this limitation can be termed as not a major drawback.

More importantly, the underlying architecture of the presented model is based on object-oriented approach utilizing graphical objects for coding. This affords the model user with the opportunity to easily comprehend and hence modify the model structure according to their specific requirements. Finally, the model is equipped with

a user-friendly interface where the values for various parameters can be easily manipulated and simulations run accordingly without a major effort.

Model Description

The simulation model is developed using research version 7.0.2 of Stella® software⁷ (Richmond, 2001). Stella® is an object oriented modelling and simulation software used extensively for building simulation models⁸. The basic building blocks of a model in Stella® are: stocks, flows, converters, and connectors (Figure 1).

Stocks are accumulations of physical and nonphysical quantities. For example, the volume of demolished pavement material lying in a heap awaiting to be hauled. The value of a stock can be traced at any point in time and persists even when activities cease to continue. The activities in turn, are represented by flows which are used to transport quantities into or out of stocks and can change instantaneously. Examples of flows include the demolition process of a pavement and the movement of machinery from idle state to working or vice versa. Connectors are shaped as arrows and are used to establish relationships among various elements of a model. The circular objects, converters are used for performing algebraic operations, housing graphical functions, or exogenous variables. These building blocks were used to build the simulation model presented in this study.

The model comprises of two main levels: the model structure/map and model interface. Each of these two levels is described in detail below.

Model Structure/ Map

Figure 2 provides an overview of the overall structural layout of the model. Since the model contains numerous interconnected objects, therefore to facilitate easier navigation, the model is disaggregated into five sectors: Trucks Sector, Loaders Sector, Machinery Utilization Sector, Material Sector, and Costing Sector. Each of these sectors is explained in the following sections.

Trucks Sector

Figure 3 shows the details of Trucks Sector of the model. Besides the auxiliary objects, the main stock-flow

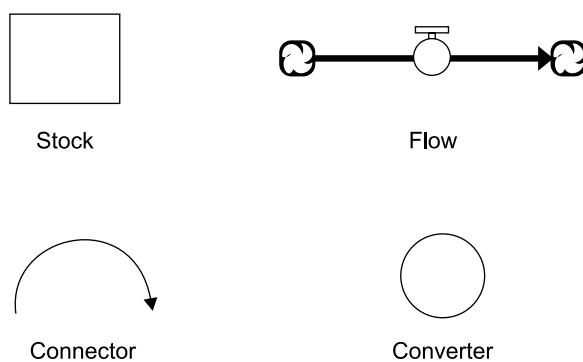


Figure 1. Building blocks of Stella models

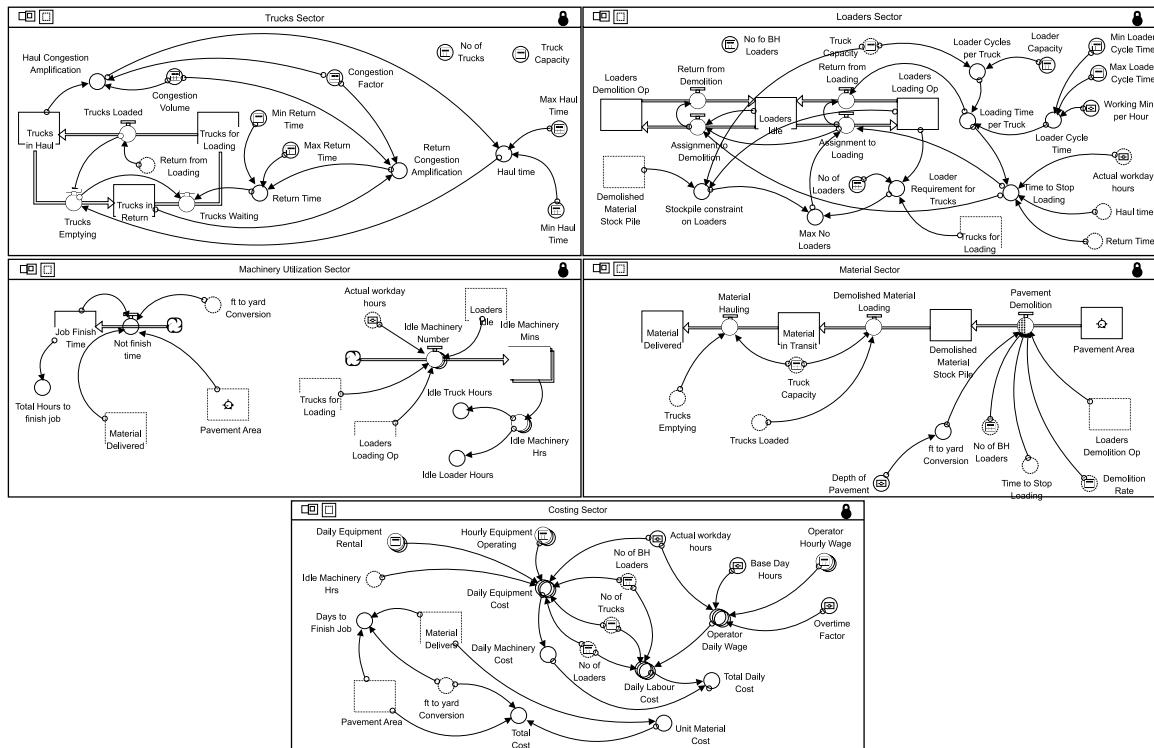


Figure 2. Model Structure/Map Level

structure in this sector keeps track of the trucks in various states such as trucks that are being loaded, the ones that are hauling the loaded material to the destination, and those which after dumping off the material are in the return journey. It should be noted that at any given time, it is possible that one or two of these stocks can have a zero value, thus, it is not necessary that all trucks have

to be engaged in all these three states simultaneously.

Inputs required for calculations in this sector include minimum and maximum times for both the haul and return journeys. Based on their respective ranges, the actual haul and return journey times are randomly sampled assuming that the journey time is uniformly

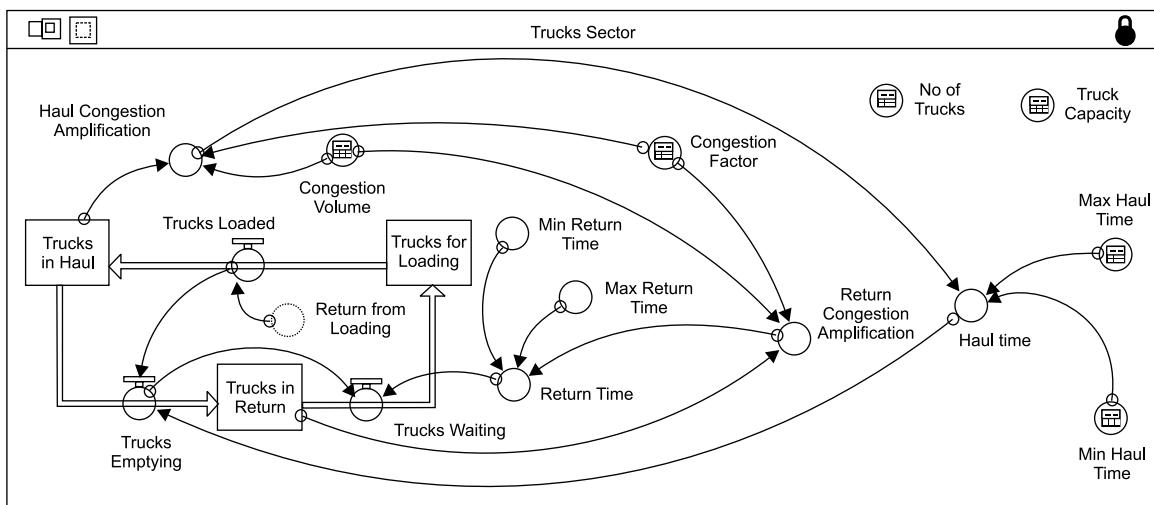


Figure 3. Trucks Sector of the simulation model

distributed between the minimum and maximum values. It is noted that the haul and return paths for the trucks between the demolition site and recycling/dump site can only have a certain capacity for the trucks traffic. If the actual number of trucks on these paths exceeds the capacity then congestion will be created, in such a scenario, a user-defined congestion factor is multiplied with the journey (haul/return) time. Other inputs for this sector include the total number of trucks engaged on the project and the carrying capacity of trucks. For simplification, it is assumed that all the trucks employed have the same capacity.

Loaders Sector

The Loaders Sector is shown in Figure 4 below. For this sector, the user has to input the number of Loaders

and Backhoe Loaders, the former being the machinery that is capable of both demolishing (removing) the pavement and uploading the demolished material onto the trucks, while the latter only has the capability to demolish pavement. Accordingly, a stock-flow structure has been provided in this sector which assigns Loaders to any of three kinds of states: engaged in uploading material onto the trucks, in idle state, or engaged in demolishing the pavement along with the backhoe loaders. The logics used to determine these states is based on the quantity of stockpiled demolished material that can be loaded onto the trucks, the number of trucks awaiting loading, and the total number of loaders. If the number of total loaders exceeds that is required for loading the stockpile onto the waiting trucks then the surplus loaders go into the idle state. If some pavement section still remains to be demolished, then the idle loaders are assigned to the

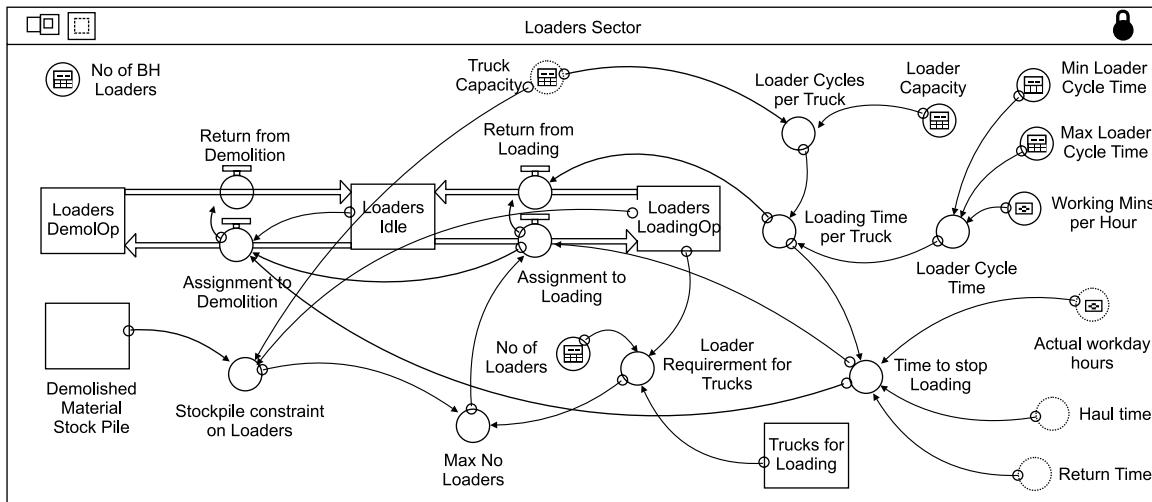


Figure 4. Loaders Sector of the simulation model

demolition job along with the backhoe loaders. However, the priority job for loaders is still loading of trucks, so if more trucks arrive and demolished material is available to be loaded, then the loaders engaged in demolition operations are engaged in the loading operation again.

A loader's cycle time is the time (minutes) in which a loader scoops up material from the stock pile, lift and swing it over the truck, empty the material into the truck and return towards the stockpile again. To account for randomness in this operation, a user has to provide the minimum and maximum cycle times and the model then samples cycle time from a uniform distribution within

these limits at each time step of the simulation. For simplification, it is assumed that all the loaders have the same cycle time and volumetric capacity. The dashed objects Haul time and Return time belong to the Trucks Sector and are described in the corresponding sector.

Machinery Utilization Sector

The Machinery Utilization Sector is shown in Figure 5 below. Two main tasks are performed within this sector: the total time to finish the job including both demolition of the pavement and the hauling of removed pavement material from the site to the destination; and the idle

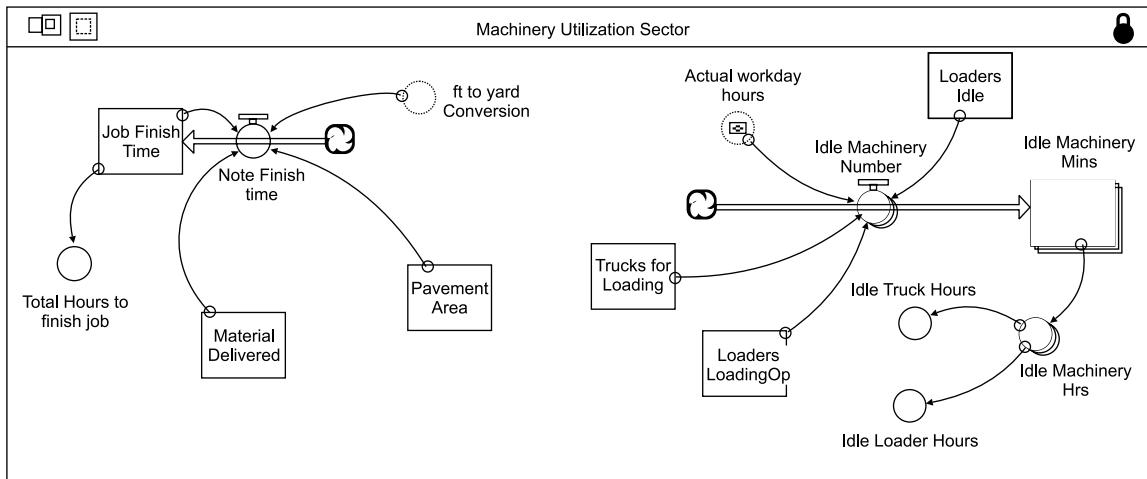


Figure 5. Machinery Utilization Sector of the simulation model

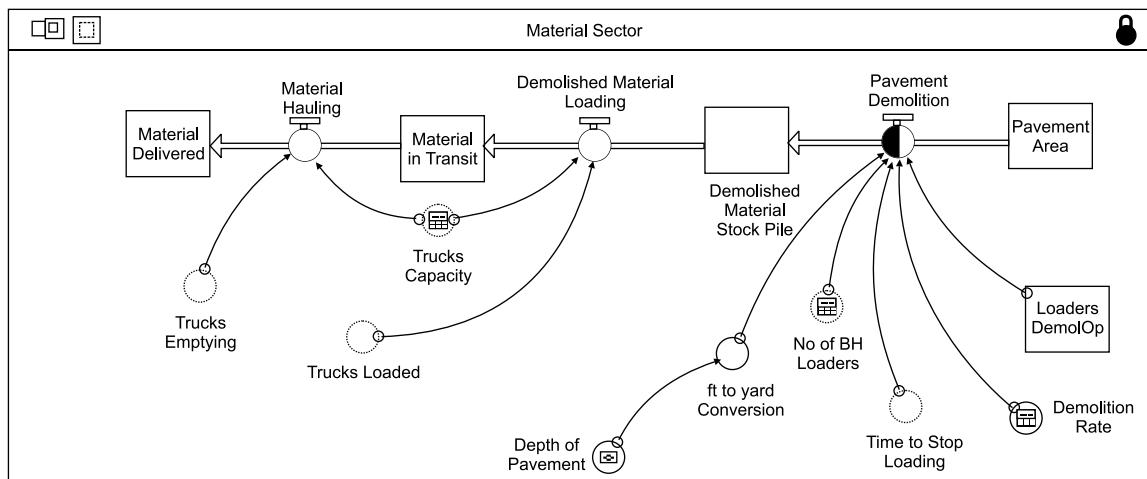


Figure 6. Material Sector of the simulation model

time, each for the trucks and loaders, during which these machineries are not working. Idle time for any machinery represents an expense to the project (equipment rental, operator wages) while not being engaged in any productive activity. In other words, idle time represents poor selection and planning of machinery utilization.

Material Sector

The stock-flow chain structure included in the Material Sector (shown in Figure 6 above) models the demolition and transport of the pavement, from the intact state to the final destination. Pavement Demolition is the rate at which the intact pavement is removed and the excavated material is stored as a stockpile on site. This rate is a function of the number of backhoe loaders and loaders

(assigned to demolition) and their production rate. The stockpiled material is then loaded onto the trucks at a rate which is a function of the volumetric capacity of the trucks and the number of trucks that are waiting to be loaded. After time delay that represents the haul journey time, the trucks are emptied at the destination and the stock Material Delivered represents the total volume of demolished pavement material that has reached the destination.

Costing Sector

The last sector of the simulation model is the Costing Sector, shown in Figure 7 above. In this sector, the total costs for the project under various heads are calculated. Total costs comprise of machinery costs and labour

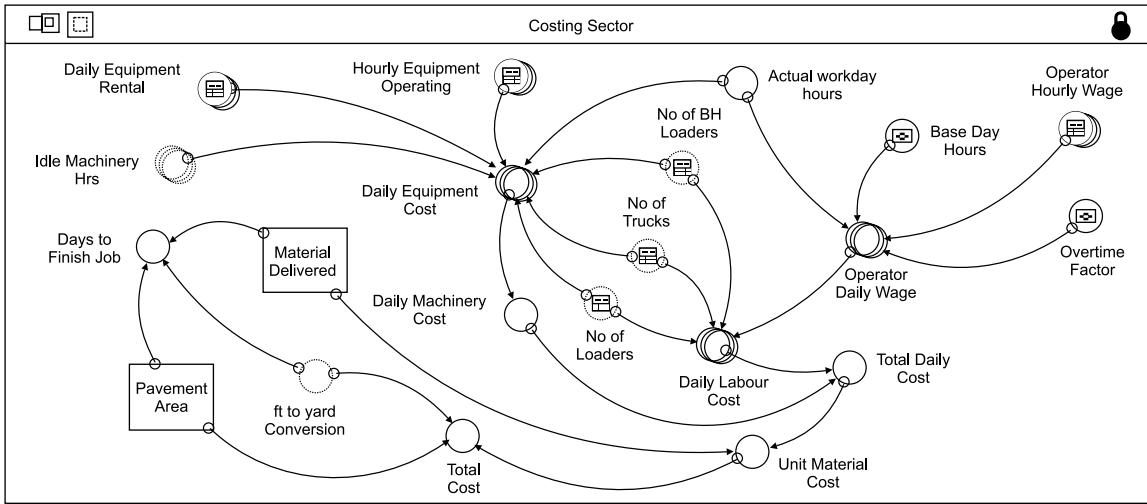


Figure 7. Costing Sector of the simulation model

costs. Machinery costs are further categorized into rental costs and operating costs. The latter category requires as input the oil/fuel costs, for each type of machinery, spent per hour while the machinery is running. Labour costs are calculated per day regardless of whether a piece of machinery is being operated or remains idle during any time of the day. Thus, the model is capable of tracking the rental and labour costs when machinery is being underutilized (idle hours). When the daily work hours exceed the specified hours of a normal day, then overtime charges for the additional time are also included

in the labour costs.

Model Interface

The model has been developed for assisting industry professionals in their daily job responsibilities. Hence, one objective in model development was to provide a user friendly interface that enables easy use of the model even without a mastery of the underlying structural formulation of the model itself. A screenshot of the user interface level of the model is shown in **Figure 8**.

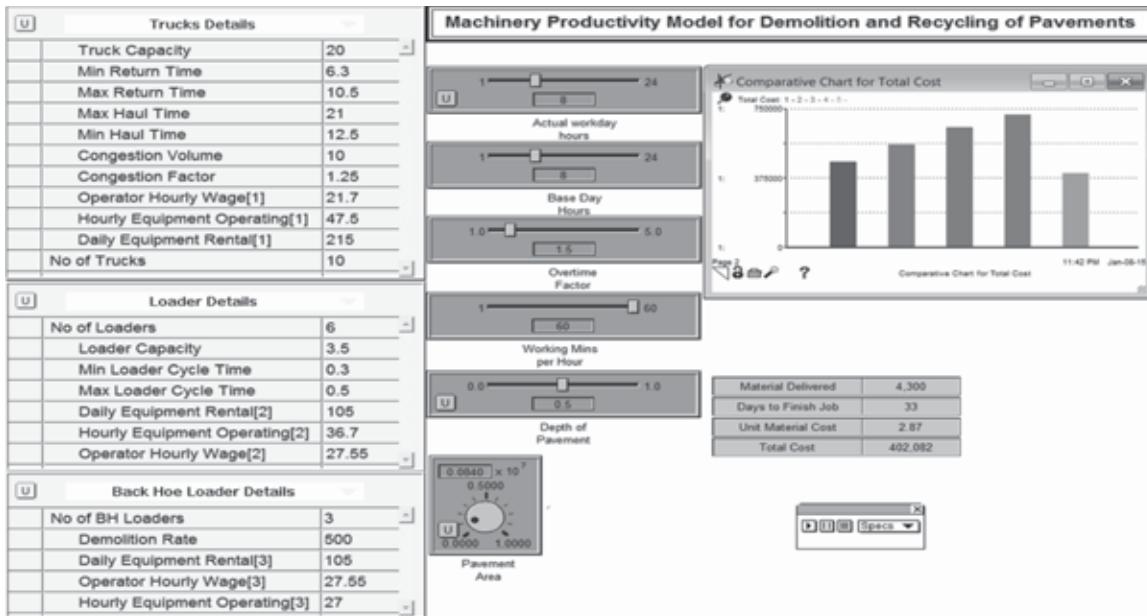


Figure 8. Interface Level of the simulation model

This interface level has several user friendly input and output devices. Information about the various features of machinery can be provided through the list input devices. Slider input devices can be used for providing information to the model about actual workday hours, base day hours (which by default is 8 but can be varied), overtime factor and hour efficiency. The overtime factor is used by the model to calculate the labour costs at the increased overtime rate for working additional hours beyond the usual eight hours workday. Initial stock of material that has to be demolished/ removed is provided using a knob input device while the depth of layer to be removed is entered using a slider input device. Key model results such as unit material cost, quantity of delivered material, number of days to finish the total job, and total cost is displayed in real time during simulations using numeric displays. A variety of graphic output displays help in visually following the simulation results using time series graphs, bar charts and scatter plots etc. These graphs are also helpful in quickly reviewing results of sensitivity analyses. More detailed results about any model variable can be viewed using the tabular output device. Such tables provide values of required parameters at every instant in the simulation.

Case Study

To demonstrate utility of the developed model, a case study example is provided hereunder. The demonstration case study is chosen as reconstruction of an existing runway. The runway is about 6,000 feet long and 150 feet wide, and was constructed 30 years ago. It went under routine maintenance and rehabilitation works over the course of time. However, the condition has deteriorated to the point where it may cause safety problems for the aeroplanes.

It should be noted that for a problem of this kind several alternative options can be considered. It is assumed that an option is selected that involves removal and recycling of the existing runway pavement and reconstructing with asphalt concrete surface or with plain cement concrete pavement. In either option, the following major work items would be involved:

- Removal and reclamation of asphalt pavement and base course;

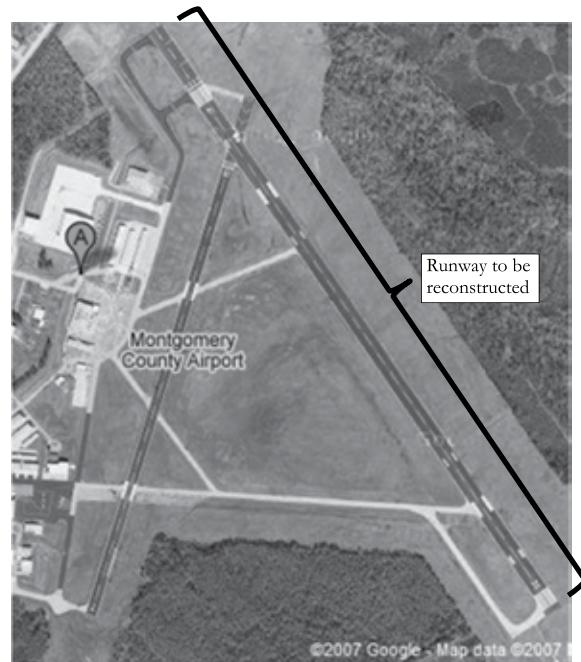


Figure 9. Aerial view of the demonstration case study runway

- Subgrade preparation and treatment with Lime-Flyash;
- Construction of cement treated base (CTB) course; and
- Construction of PCC or asphalt concrete surface course

To illustrate the utility of the developed model, further discussion below is limited to the removal and reclamation of asphalt pavement and base course only. Because this item affords the possibility of a creative and original

4" to 5" asphalt cement
2" to 3" asphalt cement with iron ore aggregate
9" to 13" iron ore with silty sand (cement treated)
2" to 7" iron ore and silty sand
X X Lime and Fly ash stabilized sub-grade

Figure 10. Structural layers of the existing runway pavement

approach wherein the choice and capacity of machinery can be optimized using the developed model.

In the case study, the existing runway pavement has a total thickness of 26 inches, comprising of various layers as shown in Figure 10 below.

Reclamation and recycling of asphalt pavements involve removal of the existing pavement, reducing recycled materials to a suitable size for reprocessing, blending the reclaimed material with virgin aggregates and liquid asphalt and relaying the materials as a base, or surface course⁹. The removal of old pavement can be accomplished by either cold-milling or planning or alternatively by ripping and crushing. Peurifoy et al.¹⁰ prefer the use of the former method for the reason that it allows the restoration of the pavement section while eliminating the need to change the grade. This method is also preferred when only the surface course has to be removed and relaid without disturbing the underlying base course. However, this method is not considered in this case study because of two reasons: first, no reliable sources for estimating production of milling machine could be obtained and, secondly, the project involves not only removal of asphalt surface course but the base course as well. Hence, the option of offsite recycling is adapted in this study.

It is assumed that removal of pavement layers would be accomplished with the help of backhoe loader equipped with pavement removal bucket and assisted by demolition hammer. The excavated pavement would be loaded onto dump trucks using front end loaders which in turn will haul the material to asphalt plant for recycling and future reuse. It is assumed that a hot mix asphalt plant is located at a distance of 5.6 kilometres from the project site. The production rate for this equipment combination is adapted from RS Means¹¹. It may be noted that pavement removal can also be accomplished by using rippers attached to dozers, however these are not considered due to lack of information about production rates.

Another constraint worth mentioning is that the removal of pavement cannot be carried out sequentially by first excavating the whole of pavement, dumping it on site, and then hauling the excavated material later on. This is due to the requirement that stockpiling of crushed reclaimed asphalt pavement (RAP) has to be

kept as short as possible in order to avoid consolidation of the material and retention of moisture¹². Therefore, excavation, loading, and hauling of the RAP will have to proceed as concurrent activities.

It can be noted that a large number of machinery combinations are possible to choose from in terms of the capacities and number of equipment that could be employed for these works. Furthermore, the cycle times of excavation, loading, and hauling units should not be treated as fixed values but rather the probabilistic distribution of these variables should be taken into account. For these reasons, the developed simulation model can be a useful tool.

Model Simulations

Simulations were performed several times while altering the values of key variables. Sensitivity analysis was performed to study the behaviour of key model parameters while altering the values of chosen variables. All those results cannot be reproduced herein due to space constraints but a few sample results are presented and discussed.

Employing two loaders of 3.5 cy capacity dedicatedly for pavement removal only and another two loaders of same capacity with dual functions of pavement removal as well as loading of trucks, a sensitivity analysis was performed to investigate the variation of total cost with the number of trucks. Ten simulation runs were made starting from 2 trucks and increasing incrementally to a final number of ten trucks. Figure 11 shows the results of these runs. It can be seen that the total cost is higher for 2 trucks and starts decreasing with increasing number of

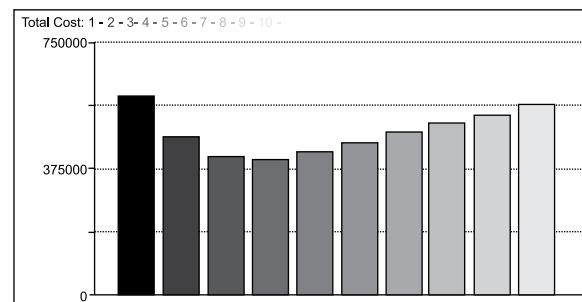


Figure 11. Sensitivity analysis of total cost for number of trucks

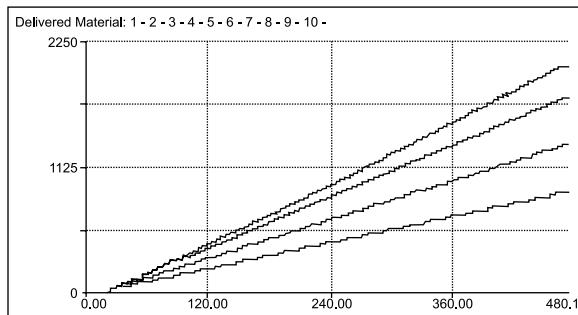


Figure 12. Sensitivity analysis of delivered material for number of trucks

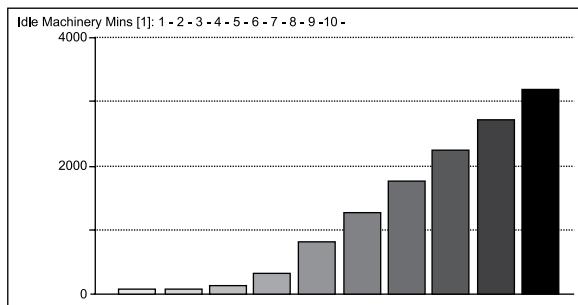


Figure 13. Idle truck minutes

trucks until it reaches a low value for 5 trucks. Thereafter, increased number of trucks results in increased total costs.

The above results can be further explained if we consider the amount of pavement material removed and delivered to the recycling plant in a single day. Figure 12 shows that the amount of delivered material increases with rising number of trucks (curves 1 to 4). However, beyond five trucks, the delivered material remains the same (indicated by curves 5 through 10 all of which are overlapped). This happens because of constraint on production of material for delivery i.e. pavement removal. Beyond five trucks, sufficient material is not present for loading & hauling, and hence those trucks essentially remain idle for most of the time (Figure 13), contributing little or none to production but raising the total cost. Hence, it can be deduced that for (2+2) loaders, the optimum number of trucks is 5.

For investigating a few more combination of machinery, more simulations can be run while keeping number of trucks as five and varying the number of excavators engaged in pavement removal from 2 to 10. The resulting total costs are shown in Figure 14 which indicates the total costs reach a low value for six loaders (shown by bar numbered 5). Beyond six loaders, the number of

trucks becomes a constraining factor since the stockpile of excavated material keeps on accumulating while sufficient trucks are not available to haul the same.

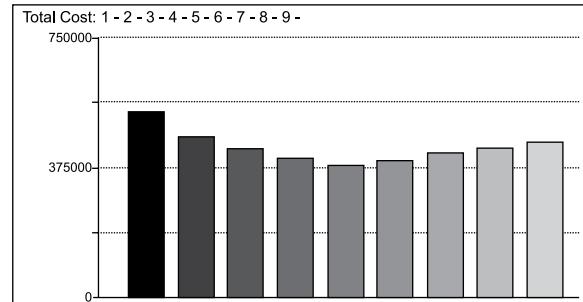


Figure 14. Sensitivity results of total cost with number of excavators

Table 1. Selection of machinery for the case study.

Work Item	Equipment Description	Number	Days Engaged
Reclamation of existing runway pavement	Backhoe excavators with 3.5 cy pavement removal 20 cy dump truck	4 5	69 69

Further investigations could be made to look into the combinations of six excavators with various numbers of trucks. However, as noted above, the problem essentially becomes a multi-objective optimization model and may need a large number of simulations to arrive at the best possible solution. For the purposes of this case study, four backhoe loader excavators equipped with pavement removal buckets are chosen. Two of these will always be engaged in the pavement removal process while the other two will occasionally assist in excavation when they are not busy loading the trucks. Five trucks are selected each with a capacity of 20 cubic yards. With this combination, the total job of pavement removal and hauling can be finished in 69 days (Table 1).

CONCLUSIONS

A novel heavy machinery selection tool for pavements demolition and recycling projects is developed. The tool is based on the System Dynamics methodology whose visual model structure allows easy coding even by novice users. But the real utility of the model lies in its user-friendly interface which enables industry professionals to employ the model for their job tasks even without requiring any deep understanding of the model structure.

Using a demonstration case study, the utility of the model was shown whereby alternative scenarios based on different combinations of machinery (number, capacity, and other characteristics) were quickly explored and compared. It was shown that based on the choices available to the site manager, near optimal solutions can be very quickly determined using the developed model. It was shown that model simulations can help in identifying the critical variables which can enhance productivity significantly or studying the effects of variables which can easily be controlled at the job site.

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