Time-Cost Tradeoff Model for Multiple Asphalt Paving Projects Using Genetic Algorithms

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Abstract

Road construction companies work on delivering multiple projects at the same time. Careful planning and allocation of each project's resources need to be determined and evaluated in order to minimize their costs and maximize their profits. In this paper, a model was developed with the objective of trading off between time and cost for Multiple Paving Projects using Genetic algorithms (MPP-GA). The MPP-GA was designed with four different modules: (1) an input module that requires the number of multiple projects in hand and their related information; including each project's contractual milestones and construction specifications. (2) An equipment database module that contains a list of the available different types of equipment used on paving projects including their production rates and their cost. (3) an Optimization engine module that works to determine the optimum equipment fleet required to be allocated on each paving project based on the total equipment cost. The optimization module performs a trade-off between the cost of resources allocated for each project and the delay damages and/or incentives calculated as a result of late, early or on time delivery of each project. and finally, (4) an output module that reports the fleet configuration, delay damages and/or incentives, total cost and expected finishing dates for each project. A case study was presented to illustrate a number of practical features of the proposed model and to demonstrate its capabilities in selecting the near optimum fleet configuration.

Keywords –

Paving Projects; Multiple Project; Resource Allocation; Optimization; Genetic Algorithms; Construction Planning.

1 Introduction

Asphalt paving projects require the use of a set of heavy equipment including asphalt batching plants, mechanical pavers, vibratory rollers, pneumatic rollers and haulers. The typical construction sequence for paving asphalt roads starts by first producing hot-mix asphalt at an asphalt batch plant. For large jobsites, contractors set up the asphalt batch plants on/near the jobsite to minimize the hauling time and, hence, the cost from the production to the discharge location. Second, produced hot-mix asphalt is discharged into trucks which are hauled to the jobsite. Trucks loaded with asphalt feed the paver finisher which spreads uniformly thick layers of asphalt mix. Finally, vibratory rollers apply compaction to reach the required density of the road layers and then pneumatic rollers are used to smooth the finalized asphalt road.

The majority of contractors work on multiple paving projects, where every project has its own specifications, conditions and requirements. However, many contractors fail to plan and allocate their resources on their concurrent projects and hence they fail to deliver their project on time which leads the employer to impose delay damages on the contractor, or they allocate extra resources to avoid late delivery and hence extra cost of resources which in turn reduce their profit. Optimization models are one of the widely used techniques for approaching resources allocation problems. Optimization models can be developed using either traditional methods like linear programming, integer programming, dynamic programming…etc. or un-traditional methods like genetic algorithms, particle swarm, ant colony…etc. Traditional optimization models are inappropriate for resources allocation in paving projects due to their complexity and the presence of many variables and constraints, therefore un-traditional optimization methods are suitable for this problem.

Genetic algorithms (GAs) are widely used technique in optimizing the allocation and utilization of resources in construction industry [1].

2 Literature Review

Efficiently selecting the number of equipment to be used on each highway project or section is a resource allocation optimization problem. Different studies throughout the literature have tackled the use of different optimization techniques to provide near optimum solutions to resource allocation.

Hegazy [1] introduced a technique for solving the resource allocation and levelling problem using Genetic Algorithms (GAs) by searching for near-optimum solution. The developed technique defines priorities to selected tasks based on their impact on the schedule. The GA searches for an optimum set of tasks' priorities that produce shorter project duration and better-levelled resource profiles. Hegazy's work concluded that the use of GA in solving the resource allocation problem can be done by incorporating multi-objectives to the model; such as: selecting the appropriate methods of construction for each activity, considering the daily penalty of exceeding the deadline as well as the incentive for early completion. The work was generic and it does not consider the idea of allocating the resources on multiple projects.

Hassan and Gruber [2] developed a simulation model for simulating an asphalt paving project to optimize costs & time using STROBOSCOPE software. A sensitivity analysis was performed to estimate the effect of resources on costs & productivity. The model considered only one project, in addition sensitivity analysis is not an efficient method for determining the optimum fleet configuration.

A study by Heon Jun and El-Rayes [3] developed a multi-objective optimization model using GA that is capable of measuring and minimizing the undesirable resource fluctuations. The model's objective was set to maximize resource utilization efficiency and minimize project duration while complying with all precedence relationships and resource availability constraints. The authors concluded that the use of a multi-objective resource utilization function generates a trade-off. In this case, between minimizing the overall project duration while maximizing the resource utilization efficiency.

Kane and Tiesser [4] developed a mathematical optimization model that was used in the planning of a multi-project program. The working principle of their model was that the costs of completing a group of linked projects were optimized by speeding up the realization of the whole program to save time. The model was validated via a case study of three concurrent projects, each with a different duration, budget, number of operators and quantities of work. Resources were effectively allocated to minimize the costs and accelerate the project time. However, the model was limited to the allocation of human resources only.

Sarkar and Shah [5] developed a framework for the application of genetic algorithms to optimize the productivity of the site excavation activities for highway construction project using two types of equipment: hydraulic excavators and tandem vibratory rollers. The model was coded on MS-Excel and Evolver add-in was used as the GA optimization engine. They compared the actual resource allocation done on the project with the allocation output from the GA model and observed the results. It was concluded from their model that the resource allocation done by the GA produced an increase of 15.7% of the total productivity of the project compared to the manual allocation. However, the model did not consider the paving activities for road construction.

After reviewing the previous studies, it can be concluded that the previous studies were mainly discussing resource utilization for construction projects in general. In addition, the optimization models for asphalt paving projects were done on a single project scale and not applied on multiple one.

3 Objective & Scope

Since Highway projects is comprised of several and wide range of activities that include excavation, backfilling, grading, paving, compacting…etc. This paper will highlight and focus on the paving package as an activity of paramount importance for the project completion.

This paper presents a time-cost trade-off model to aid contractors in allocating their resources on multiple paving projects. The proposed model will report the fleet configuration for each project, finishing date, equipment costs, delay damages and incentives (if any).

4 MPP-GA Framework

A model was developed that is comprised of a four modules: input, equipment database, optimization engine and output as shown in figure 1. The developed model was coded on MS-Excel & Visual basic for Applications (VBA) to facilitate the user inputs and the output reports.

The input module compiles information such as project description, contract information…etc. such inputs are fed along with a pool of equipment with their information and specifications into the optimization engine module. The model's engine works on providing the optimal allocation of resources on each project by providing a time-cost trade-off.

Finally, the results are transferred to the output module which generates a number of outputs per project including: (1) equipment fleet configuration, (2) actual project finishing dates, (3) total projects cost and (4) amount of incentives/delay damages if any.

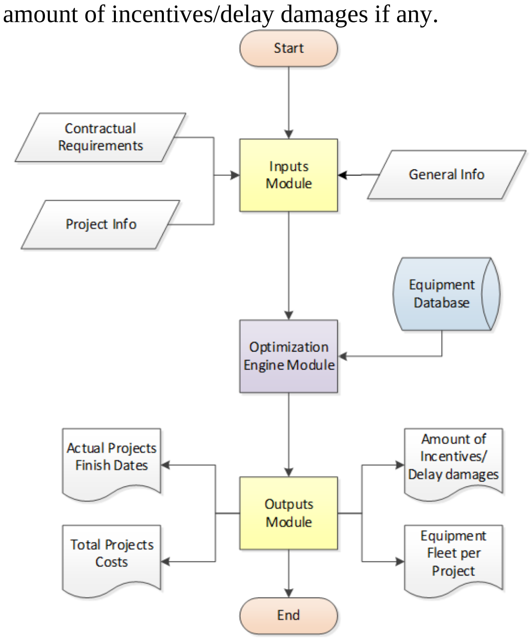

Figure 1: MPP-GA Framework

4.1 Module 1: Inputs Module

4.1.1 Project Information

In this part the user specifies some inputs including the number of the multiple projects in hand and their related information.

The volume of work required for each project (n) was calculated based on its designed specifications in terms of Length (Ln), Width (Wn), Thickness (Thn) and Density of Asphalt (Dn), which is assumed to be 2.4 ton/m3.Thus, the quantity of work was calculated (see Equation (1)).

$$Qn = Ln\ x\ Wn\ x\ Thn\ x\ Dn \qquad (1)$$

4.1.2 Contract Information

Each project has to be set with a target completion date expressed in number of weeks to complete the required work. In the event of surpassing the target completion duration for any project a penalty ($/week) is incurred for each day surpassed by the completion date. On the other hand, in the event of concluding the project prior to the completion date, an incentive ($/week) can be given to the appointed contractor. Based on the contract terms and conditions for each project, the end user defines the amount of delay damages and incentives for as well as the target competition duration for each project.

4.1.3 General Information

Other inputs include the hauling and return speed of trucks as well as the distance between the nearest asphalt batch plant and the project. However, several assumptions were considered in MPP-GA that includes the following: (1) grade resistance for the roadway between the asphalt plant and the project location are not considered in trucks cycle time and hence in the trucks production rates, (2) the efficiency of each construction equipment are determined by the user and considered constant throughout the project duration.

4.2 Module 2: Equipment Database

A database was designed to include five different equipment used in any paving project including: asphalt batch plants, trucks, mechanical asphalt paver, tandem vibratory rollers, and pneumatic rollers. An extract for the equipment database module in this model is demonstrated in table 1.

Table 1: Equipment Database Extract

ID	Equipment Type	Available No.	Production rate (ton/hr)	Cost/hour ($/hr)	Model no.
TR1	Truck	7	25.2	$65	Mack CH613
TR6	Truck	8	30.1	$70	Mack RD688
M1	Asphalt plant	2	168	$680	Tarmac HRODC_AP1
M3	Asphalt plant	3	67	$530	Tarmac HRODC_AP10
PAV-1	Asphalt paver	3	425	$280	DYNAPAC F800T
TV-1	Tandem Roller	5	224	$57	CAT-CB-534D XW
PNR-1	Pneumatic Roller	6	251	$55	CAT-PS150C

The production rates for each type of equipment were retrieved from either manufacturer's catalogs or field experts. The ownership cost & operating cost were calculated in order to end up with the rate per hour [6]. The production rates for rollers were converted from cubic yard per hour (see Equation (2)) to ton/hour (Equation (3)) [7].

$$Cubic\ Yard/hr = (16.3\ \times W \times S \times L \times E) \div P \qquad (2)$$

Where, (P) is the number of passes required, (W) is the width compacted in feet, (S) is the Roller speed in mph, (L) is the Lift thickness in (in) and E is the Efficiency.

$$Ton/hr = Cubic\ Yard/hr \times 0.7645 \times Dn \quad (3)$$

Where, (0.7645) is a constant for converting to cubic meters/hr.

4.3 Module 3: Optimization Engine

This module is the engine of the model where all the calculations are made. Since the resource allocation problems for paving projects is quite complex problem, genetic algorithm was used to solve our problem since it is a powerful optimization algorithm that deals with combinatorial-in-nature problems.

Genetic algorithms (GAs) are search algorithms developed by Holland in 1975, which are based on the mechanics of natural selection and genetics to search through decision space for optimal solutions [8]. Over the last two decades, these search algorithms have gained significant popularity in engineering fields [9].

Palisade (2015) Evolver™ v7 is a MS-Excel add-in that utilizes genetic algorithms in optimization. The GAs engine performs operations in sequential steps: (1) an initial population of solutions is created and is composed of a number of chromosomes as shown in table 2

Table 2: Chromosome Representation

Plants					Trucks						Pavers				Tandem Rollers			Pneumatic Rollers		
M1	M2	M3	M4	M5	TR1	TR2	TR3	TR4	TR5	TR6	PAV-1	PAV-2	PAV-3	PAV-4	TV-1	TV-2	TV-3	PNR-1	PNR-2	PNR-3
1	1	0	0	0	4	3	0	1	0	0	1	0	0	0	1	1	0	1	0	0

Each gene in the chromosome structure represents the number of equipment required per project duration. The domain of variables for the genes is a set of integer numbers that have a range equal to the number of equipment per type from Module 2: Equipment Database. (2) A fitness function is used to evaluate the pool of chromosomes (see Equation (4)).

$$Minimize.\ Total\ Cost = \sum_{j=1}^{w}\sum_{i=1}^{p}(EHC\ x\ NH\ x\ NE)\ +\ DLn\ -\ In \quad (4)$$

Where p= total number of projects, i=project number, w= total number of weeks, j=week number, (EHC) is the equipment hourly cost ($/hour), (NH) is the number of hours worked by each equipment, (NE) is the number of equipment for each type, (DLn) is the delay damage per project and (In) is the incentive per project.

The executed quantities at the end of each week are recorded, if the executed quantity was equal to the required quantity at the planned finishing date then the project was finished as scheduled and hence neither delay damage nor incentive will imposed or gained respectively. However, if the executed quantity was more than the required quantity at the planned finishing date, then the project was finished earlier and the model will provide the actual finishing date. On the other hand, if the executed quantity was less than the required quantity then the project is behind the schedule & extra duration will be calculated based on equation 5.

$$ED = rQ - eQ/\ Pa \quad (5)$$

Where (ED) is the extra duration in (weeks), (rQ) is the required quantity of asphalt to deliver per project in (tons), (eQ) is the actual executed asphalt quantity as scheduled by the model in (tons/week) and Pa is the average production rate during the project execution by the governing resource which is the asphalt batch plant in (tons/week).

The total delay damage incurred will be calculated using equation 6

$$DLn\ (\$) = ED\ \times\ D \quad (6)$$

Where (DLn) is the total damages incurred, (ED) is the extra duration in (weeks), (D) is the contractual delay damage per week per project.

The total incentive earned in case of early finish will be calculated using equation 7.

$$In(\$) = (PD - FD) * I \quad (7)$$

Where (In) is the total incentive earned, (PD) is the planned finishing date specified by the user in weeks, (FD) is the actual finishing from MPP-GA model in weeks, (I) is the contractual incentive specified in the contract entered by the user.

Then the actual finish date for delayed projects can also be calculated using Equation (8).

$$aF = ED + pF \quad (8)$$

Where (aF) is the actual finish date and (pF) is the planned finish date of the project.

(3) Genetic operators (selection, crossover, and mutation) are performed on the number of chromosomes and evaluating the fitness function to determine the fit solutions replace the weak solutions; thus a new population of solutions is formed and so on.

A group of constraints were considered in developing MPP-GA including: (1) the cumulative production rate for trucks, pavers and rollers should cover that of asphalt plants. (2) The number of equipment used should not exceed the available number. (3) A soft constraint was included that makes sure that cumulative executed quantity delivered should be equal or greater than the required quantity to finish the project.

4.4 Module 4: Output Module

This module produces the outputs generated by the GA engine on the developed reporting user interface which includes: (1) the set of equipment fleet to be used per project per week, the total projects costs, the actual finish dates per project and the amounts of incentive or delays per project that were expected to be incurred.

5 Case Study

A hypothetical example is considered to illustrate the use of the developed model in selecting near-optimum fleet configurations from a set of scenarios. It also demonstrates the ability of the model in conducting time–cost trade-off analysis. Figure 2 & 3 show the projects location and description respectively.

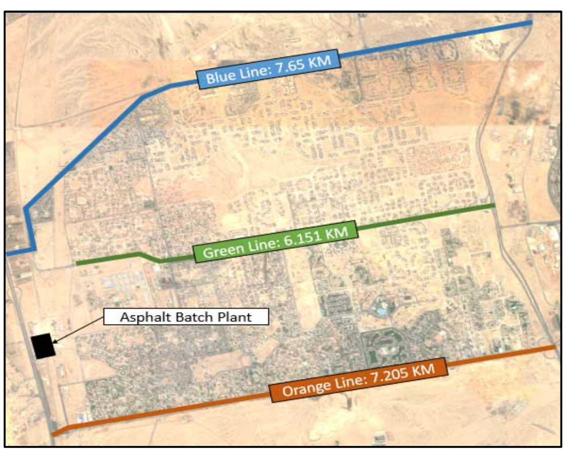

Figure 2: Projects Location and Description

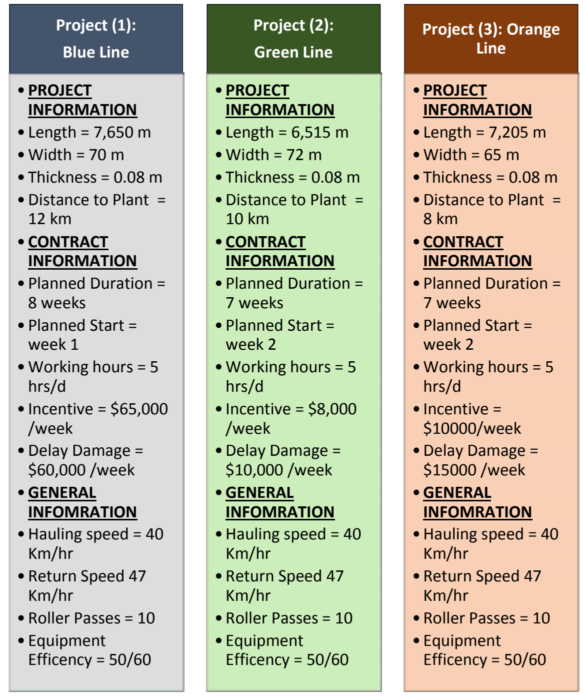

Figure 3: Case Study inputs for the three projects

The user will enter the projects details using the MPP-GA interface that include the roads dimensions, contract duration, commencement date, working hours, equipment efficiency…etc. Figure 4 shows a sample for the user's input for project 1 using MPP-GA interface.

Figure 4: MPP-GA inputs module with Project (1) inputs defined by the user.

The fitness function was originally set to minimize the total cost of all projects while satisfying the set of constraints as defined in the model engine. The GA initial solutions' pool was set to be 1000 solutions, the termination criteria was set to be completing 200,000 trials, the crossover rate was set to 90% and the mutation rate was set to 10%.

6 Results and Discussion

The total cost after optimization was almost $ 2.07 million which includes the cost of resources allocated to the three projects, incentives earned and delay damages incurred. Figure 5 shows Evolver's progress after 50,000 trials.

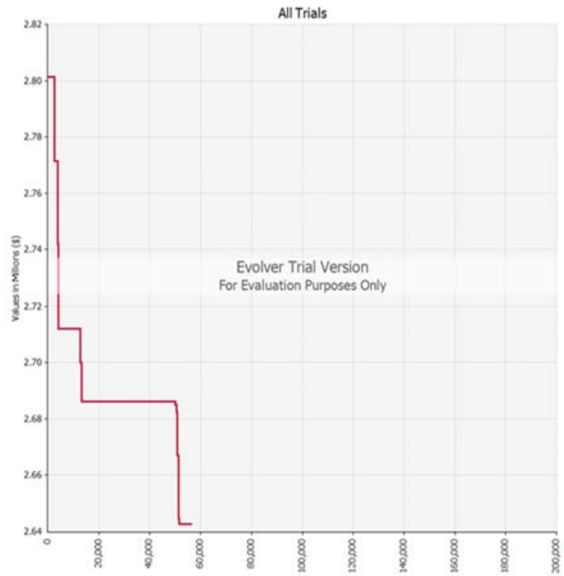

Figure 5: Solution convergence on Evolver®

Figure 6 depicted the results of MPP-GA output module for Project 1, which shows project cost, the actual finishing date, planned finishing date, delay damage, incentive & fleet configuration for Project 1 in week 4, in addition to the total projects cost.

Figure 6: Model output sample for Project 1, week 4

Table 3 summarizes the output results of MPP-GA for the three projects showing their costs, planned finishing date, actual finishing date, delay damages & incentives.

Table 3: MPP-GA Results

	Project [1] Blue Line	Project [2] Green Line	Project [3] Orange Line
Planned Finish (weeks)	8	8	7
Actual Finish (weeks)	7	10	8
Delay Damages ($)	0	$20,000	$15,000
Incentives ($)	$65,000	0	0
Project Costs (including Incentives/delay damages)	$777,473.9	$651,952.9	$648,141

It was expected that due to limited resources available, the three projects cannot be delivered on schedule. Project 1 was delivered one week earlier, while Project 2 and Project 3 were delivered later than the contract duration by two weeks and one week respectively. Project [1] has the highest delay damage and incentive compared to project [2] and [3]; consequently, avoiding delay in project [1] was preferable where the amount incurred in case of delay will be $60,000/ week while the amount incurred as result of the late delivery of project [2] & [3] was $ 35000.

The total cost for project [1] before considering incentive was $ 842,473. By including the incentive, the total cost was reduced to be $ 777,473. If project [1] was finished on week 8 as planned and the other projects [2] & [3] were finished on week 10 & week 8 respectively, the total cost for project [1] will be $ 806,465 as shown in Figure 7. The cost of allocating extra resources (mixers, haulers…etc.) to project [1] for finishing earlier was $ 36008. Consequently, the incentive earned in project [1] covered the extra resources allocated to finish earlier & contributed to cover damages incurred in the other projects. In order to finish project [2] on time (two weeks earlier), this requires allocating extra resources which will increase the cost by almost $70,000. While for project [3], extra resources that cost almost $ 45,000 to the project cost in order to deliver the project on time. Consequently, MPP-GA effectively traded of between cost and time to obtain near optimum results as explained.

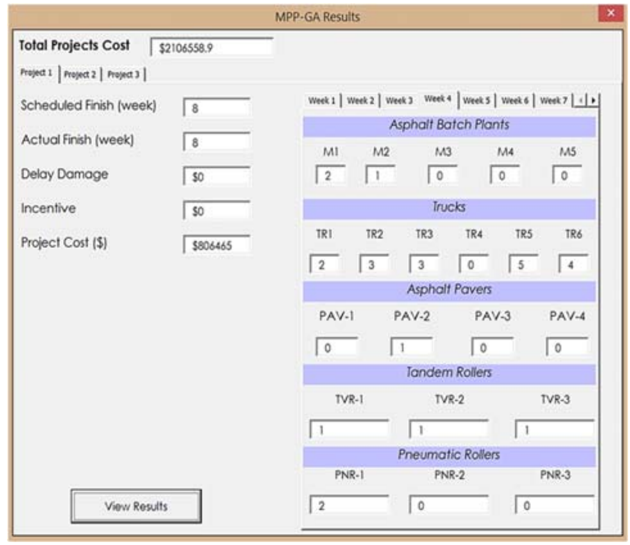

Figure 7: Model output for finishing Project 1 on time

7 Conclusion

Road construction agencies procure contractors to work on multiple projects or section simultaneously to save construction time and minimize costs. In this paper a model was developed to aid contractors in determining the optimum equipment fleet configuration to use in order to finish each project on time, within its set budget and avoid delay damages incurred as a result of surpassing the contractual finish dates. An equipment database module was incorporated into the model which included different types of paving equipment. The model uses an optimization engine coded with GA to provide the optimum equipment utilization configuration while preforming a time-cost trade-off to minimize the total costs and finishes each project on its contractual time. A case study was used to demonstrate the model’s essential features.

For further studies, a second step optimization module can be added to optimize the allocation of resources for the delayed projects during extra time, since some of the resources used for project [1] will be back to the warehouses, hence there is chance to use cheaper resources (mixer, trucks, pavers…etc.) and get the work done as required.

Moreover, 3D simulation module can be considered to simulate the construction sequence and resources movement, the 3D simulation will be beneficial to demonstrate some complexities like change in elevation, bridges, turns…etc. consequently, the model will be able to figure out the change in productivity of resources together with changes in cost.

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