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SIMULATION-BASED MODEL FOR OPTIMIZING HIGHWAYS RESURFACING OPERATIONS

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Abstract. Work zone length in the highways' resurfacing is an important factor that should be determined before the start of work. This factor influences the time and cost of the project. This paper presents a framework that is dedicated for determining the optimum length of highway resurfacing work zone. The framework estimates the total duration and total cost of resurfacing by conducting simulation analysis to model the resurfacing operations of highways to account associated uncertainties. The framework analyzes resurfacing of highways and divides them into zones. The lengths of these zones depend on minimum total cost and minimum duration. The framework consists of two modules; simulation and optimization. Simulation module is responsible for estimating total duration for each work zone. Whereas, optimization module optimizes the total cost including direct resurfacing operation, indirect/overhead costs, and the impact of work on road users' costs. The latter costs include queuing delay cost, moving delay cost, accident cost. A numerical example is presented to illustrate the practical use of the framework.

Keywords: planning, computer simulation, genetic algorithms, highways resurfacing, road users' cost.

1. Introduction

Highway maintenance, especially pavement rehabilitation or resurfacing, requires lane closures. Given the very substantial cost of maintenance and the very substantial traffic disruption and safety hazards associated with highway maintenance work, it is desirable to plan and manage the work in ways that minimize the combined cost of maintenance, traffic disruptions and accidents. Work zone delays due to highway maintenance have been increasing in reconstruction and maintenance work zone. Highway construction projects are classified as infrastructure construction projects characterized by long duration, large budget, and complexity. Resurfacing of highways is executed in different environmental conditions which raise uncertainties that influence the production rates of construction resources. These different conditions includes unusual or complex works, equipment breakdown, unfavorable weather conditions, and unexpected site conditions. Several simulation systems have been designed specifically for construction (Halpin, Riggs 1992; Martinez 1996). These systems use some form of network based on Activity Cycle Diagrams to represent the essentials of a model, and employ clock advance and event generation mechanisms based on Activity Scanning or Three-Phase Activity Scanning. These systems are designed for both simple (e.g., CYClic Operations NEtwork (CYCLONE)) and very advanced (e.g., STate and ResOurce Based Simulation of COnstruction ProcEsses (STROBOSCOPE)) modeling.

Work zones often cause traffic congestion on high volume roads. As traffic volumes increase so does work zone-related traffic congestion and so does the public demand for road agencies to decrease both their number and duration. Negative impacts on road users are minimized by bundling interventions on several interconnected road sections instead of treating each road section separately. Negative impacts on road users are quantified in user costs. The optimum work zone is the one that results in the minimum overall agency and user costs. The minimization of these costs is often the goal of corridor planning. In order to achieve this goal the interventions on each asset type (pavement, bridges, tunnels, hardware, etc.) must be bundled into optimum packages. Hajdin and Lindenmann (2007) presented a method that enables road agencies to determine optimum work zones and intervention packages. The method allows the consideration of both budget constraints and distance constraints, including maximum permissible work zone length or minimum distance between work zones. The mathematical formulation of this optimization problem is a binary.

Pavements on two-lane two-way highways are usually resurfaced by closing one lane at a time. Vehicles then

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travel in the remaining lane along the work zone, alternating directions within each control cycle. Several alternatives are evaluated, defined by the number of closed lanes and fractions of traffic diverted to alternate routes. Chen *et al.* (2005) presented an algorithm, referred to as Simulated Annealing for Uniform Alternatives with a Single Detour (SAUASD), to find the best single alternative within a resurfacing project. SAUASD is developed to search through possible mixed alternatives and their diverted fractions, to minimize total cost, further including agency cost (resurfacing cost and idling cost) and user cost (user delay cost and accident cost). Thus, traffic management plans are developed with uniform or mixed alternatives within a two-lane highway resurfacing project. Several research efforts have been made in highway maintenance and lane closures (Jiang *et al.* 2009; Lee 2009; Lukas, Borrmann 2011; Meng, Weng 2010; Meng, Weng 2013; Wang *et al.* 2002; Weng, Meng 2013; Yang *et al.* 2009). This paper presents a framework that is dedicated for determining the optimum length of highway resurfacing work zone. A numerical example is worked out to demonstrate the essential features of the proposed framework.

2. Proposed framework

The proposed framework *Resurfacing_Sim* helps contractors in planning of highway resurfacing operation. The developed framework performs planning of highways resurfacing operation and selects optimum length of work zone based on minimum total cost and total duration. These two functions are performed by two main components – simulation and optimization modules. Fig. 1 depicts a schematic diagram for the proposed framework that shows the interaction between its two components.

3. Simulation module

The developed simulation module captures the sequence of tasks involved in the resurfacing operation and the relationships between these tasks. The procedure of designing and building a simulation model are summarized in six steps as described below.

1. Break-down the operation into main processes and tasks. For each task, type of resources (i.e., materials, labor, and/or equipment) involved in its execution is identified.
2. Indicated each type of tasks, either: *Normal* or *Combi* depending on its need of resources.

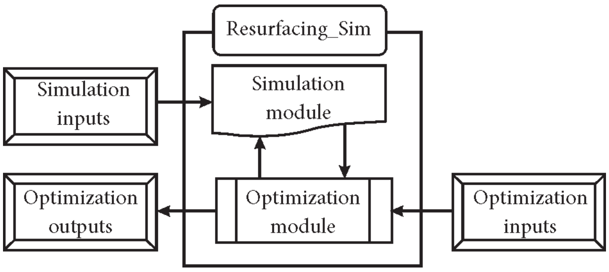

Fig. 1. Schematic diagram of proposed framework

3. Representing the sequence and relationships between tasks by using *Arcs* to map the network.
4. Add more control logical conditions by created control statements.
5. Using simulation language to code the simulation network and control statements.
6. Verify the simulation model and test it.

3.1. Modeling of converting traffic flow

Converting traffic flow involves three main processes:

I – laying safety control devices;
II – breaking concrete platform and median;
III – removing waste materials from work zone.

Fig. 2 depicts the elements of the network that capture the converting traffic flow. Table 1 and Table 2 list the resources, input parameters, and tasks which are involved in converting traffic flow.

3.2. Modeling reconstruction of semi-rigid paving

Reconstruction of semi-rigid paving involves seven main processes:

I – breaking concrete slab;
II – removing broken concrete;
III – excavating old base layer;
IV – removing old base layer;
V – laying new base layer;

Table 1. Converting traffic flow resources

Type	Resources
Labor crews	Safety
Equipment	Loader – Jack hummer – Trucks
Materials	Area of work zone – Volume of waste materials

Table 2. Converting traffic flow tasks

Process	Task	Description
Laying safety control devices	Safetydevices	Distribute safety control devices along work zone length and after work zone
Breaking concrete platform and median	BrkenPlateform	Break old platform and median
Removing waste materials from work zone	Load	Load trucks with the waste material
	Haul	Move to dump area
	Dump	Dump the waste in dump area
	Retune	Return to site area

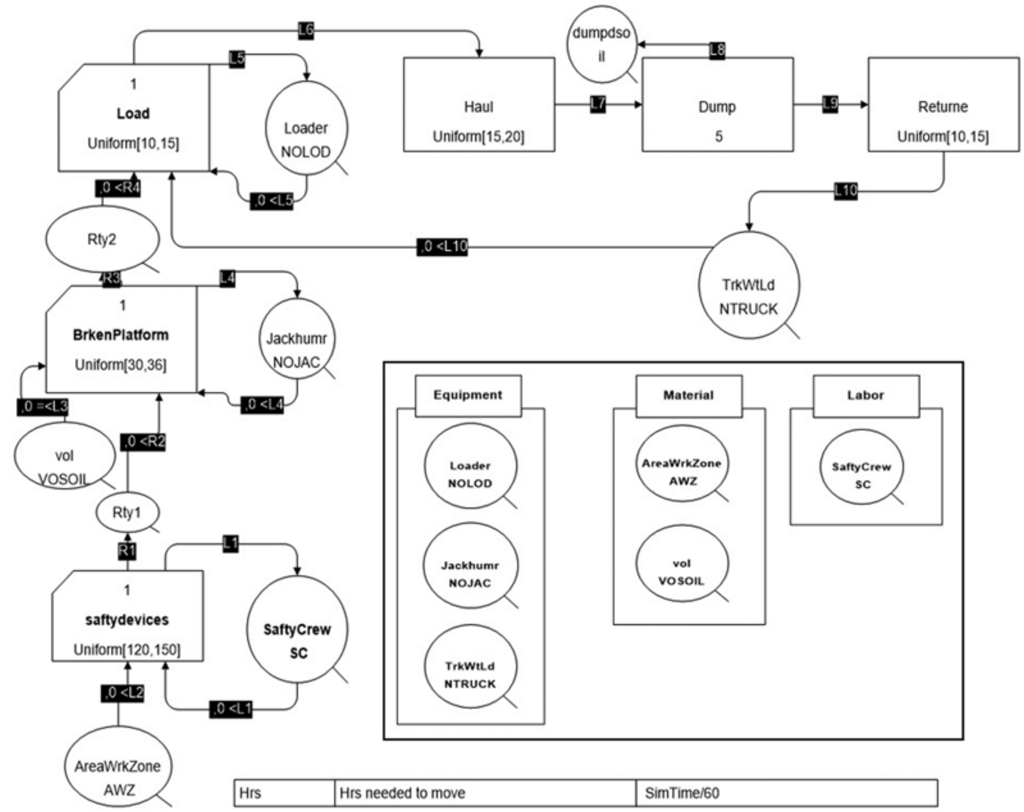

Fig. 2. Converting traffic flow simulation network

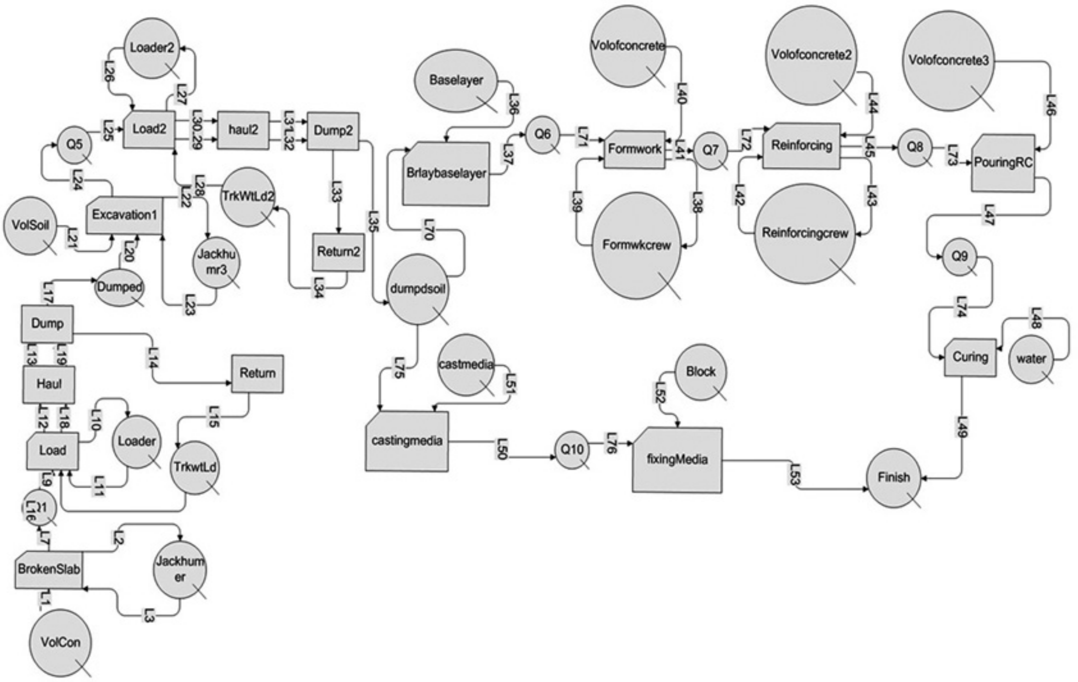

Fig. 3. Reconstruction of semi-rigid paving simulation network

VI – constructing new reinforced concrete slab, and

VII – constructing median.

Table 3 and Table 4 list the resources, input parameters, and tasks which are involved in reconstruction of semi-rigid paving. Fig. 3 depicts the element of the network that captures the reconstruction of semi-rigid paving. Similarly, tasks are performed like the manner that is descripted in converting traffic flow.

Table 3. Reconstruction of semi-rigid paving resources

Type	Resources
Labor crews	Base layer – Reinforced Bars – Formwork – Casting median – Fixing median
Equipment	Loader – Jack hummer – Trucks
Materials	Volume of waste concrete – Volume of waste soil – Base layer (crushed stone) – Blocks – Water

Table 4. Reconstruction of semi-rigid paving tasks

Process	Task	Description
Breaking concrete slab	BrokenSlab	Break old reinforced concrete slab
Removing broken concrete	Load	Load trucks with the broken concrete
	Haul	Haul to dump area
	Dump	Dump broken concrete in dump area
	Retune	Return of trucks to site
Excavating old base layer	Excavation1	Excavate base layer that is under concrete slab
Removing old base layer	Load2	Load trucks with old base layer
	Haul2	Haul to dump area
	Dump2	Dump old base layer in dump area
	Retune2	Return of trucks to site
Laying new base layer	Brlaybaselayer	Lay new crushed stone layer as a base layer for semi-rigid paving
Constructing new reinforced concrete slab	Formwork	Install slab framework
	Reinforcing	Place slab reinforcing bars
	PouringRC	Cast of concrete
	Curing	Cure concrete
Constructing median	CastingMedian	Cast median blocks
	FixingMedian	Fix median blocks

3.3. Modeling reconstruction flexible paving and finishing

Reconstruction flexible paving and finishing involves seven main processes:

I – removing old paving;
II – laying new paving;
III – installing electrical work;
IV – making drainage hole;
V – fixing sign and signal;
VI – repairing joint,
VII – finishing.

Tables 5 and 6 list the resources, input parameters, and tasks which are involved in reconstruction of flexible paving and finishing.

4. Optimization module

Optimization module utilizes Genetic Algorithms (GAs) (Coley 1999; Goldberg 1989; Holland 1992) which have been used as a powerful tool for optimization based on heuristic search techniques following random sampling. To carry out optimization utilizing Genetic Algorithms, a population is created and subjected to different GAs' operations including crossover and mutation. Crossover is utilized to combine parent chromosomes to produce children chromosomes. Crossover probability value ranges from zero to one. Usually is given a rate that ranges from 0.6 to 1. On the other hand, mutation is the process of altering some genes in a chromosome to ensure the entire state-space is searched. Mutation leads the population out of local minima. Small mutation rate (less than 0.1) is usually used (Elbeltagi *et al.* 2005). In the presence of multi- and conflicting objectives, a set of optimal solutions, instead of one optimal solution, are obtained. Multi optimal solutions exist since there is no one solution is considered as optimal for multiple conflicting objectives (Deb 2001). This module based on a biased sharing Non-Dominated Sorting Genetic Algorithm NSGA. The idea behind NSGA is that a ranking selection method is used to emphasize the non-dominant points with the aid of sharing function method to maintain diversity in the population.

4.1. Single-objective optimization

The objective of the work zone optimization problem is to minimize the total cost for work zone activities. The objective function for work zone activities is expressed as per Eq (1):

Table 5. Reconstruction flexible paving and finishing resources

Type	Resources
Labors crews	Electric – Drain – Sign – Repairing joint – Painter
Equipment	Scraper – Roller
Materials	Electric work – Drain hole – Sign – Volume of old asphalt – Volume of new asphalt – Volume of new asphalt 5 cm – Length of joint – paint

Table 6. Reconstruction flexible paving and finishing tasks

Process	Task	Description
Removing old paving	RmovingoldAsph	Removing old layer of asphalt using scrapers
Laying new paving	NewAsphalt1	Laying first layer of new asphalt that bond between base and top layers
	NewAsphalt2	Laying second layer of new asphalt that is the top layer of paving
Installing electrical work	Electricwork1	Erected the light poles and road electrical work
Making drainage hole	Draingehole	Fixing road drainage holes
Fixing sign and signal	Signandsignal	Fixing the different types of sign and electrical signal that work as a guide for drivers
Repairing joint	Repairjoint	Repairing the different types of joints that exist on road
Finishing	Finishing	Making lane limits and drawings on road using paint

$$\text{Minimize } C_T = C_M + C_U, \quad (1)$$

where: C_T – total cost; C_M – maintenance cost; C_U – user cost.

Variables that affect maintenance cost (C_M) include work zone length, fixed setup cost, and average maintenance cost per unit length. Whereas, user cost is affected by work zone length, traffic volumes, speed, etc. Both C_M and C_U are functions of work zone length since C_M and C_U are significantly influenced by work zone size. Chien *et al.* (2002), Chien and Schonfeld (2001) concluded longer zones tend to increase the user delays, but the maintenance activities can be performed more efficiently with fewer repeated setups. Since work zones lengths and maintenance duration affect maintenance and user cost, it is important to tradeoff between maintenance cost and user cost in order to minimize total cost. Maintenance cost usually includes labor cost, equipment cost, material cost and traffic management cost. The first step in estimating maintenance cost is to determine construction quantities/unit prices. Unit prices can be determined from highway agencies historical data on previously bid jobs of comparable scale (Walls, Smith 1998). In this study, the cost of maintaining for length L is assumed to be a linear as per Eq (2):

$$C_M = Z_1 + Z_2 L, \quad (2)$$

where Z_1 – the fixed cost for setting up a work zone; Z_2 – the average additional maintenance cost per work zone unit length.

The average maintenance cost per lane-km is calculated by dividing Eq (2) by the zone length L. The components of user cost are user delay cost and accident cost. The user delay can be classified into queuing delay and moving delay (Cassidy, Bertini 1999; Chien, Schonfeld 2001; Schonfeld, Chien 1999). The user delay cost is determined by multiplying the user delay by the value of user time (Wall 1998). The accident cost is related to the historical accident rate, delay, work zone configuration, and average cost per accident. Chien and Schonfeld (2001) determined accident cost from the number of accidents per 100 mln vehicle hours multiplied by the product of the user delay and average cost per accident and then divided by work zone length. The user delay cost consists of the queuing delay costs due to a one-way traffic control and the moving delay costs through work zones. The queuing delay cost C_q per maintained lane-km is the total delay per cycle Y in both directions multiplied by the number of cycles N per maintained lane-km and the users' value of time v in L.E/vh as per Eq (3):

$$C_q = YN_v, \quad (3)$$

where Y – summation of the delays (e.g., Y_1 and Y_2) incurred by traffic flows from directions 1 and 2 per cycle. Y_1 and Y_2 are derived using deterministic queuing analysis.

The moving delay cost of the traffic flow Q_1 and Q_2, denoted as C_v, is the cost increment due to the work zone. It is equal to the flow ($Q_1 + Q_2$) multiplied by:

1) the average maintenance duration per km $\left(\frac{Z_3}{L} + Z_4\right)$;

2) the travel time difference over zone length with the work zone $\left(\frac{L}{v}\right)$ and without the work zone $\left(\frac{L}{v_0}\right)$;

3) the value of time, v.

As such, the delay cost is calculated as per Eq (4):

$$C_v = (Q_1 + Q_2)\left(\frac{Z_3}{L} + Z_4\right)\left(\frac{L}{v} - \frac{L}{v_0}\right)v, \tag{4}$$

where v_0 – the speed on the original road without any work zone, km/h.

The user delay cost (C_U) is the summation of queue delay cost (C_q) and moving delay cost (C_v) as per Eq (5):

$$C_U = C_q + C_v. \tag{5}$$

The accident cost incurred by the traffic passing the work zone is determined from the number of accidents per 100 mln vehicle hours (n_a) and the average cost per accident (v_a) as per Eq (6):

$$Ca_q = \left(\frac{C_q}{v} + \frac{C_v}{v}\right)\left(\frac{n_a v_a}{10^8}\right). \tag{6}$$

Optimization variables are any entities within studied system, where any change in this entity would affect the objective function. Based on interviews with expert engineers and extensive analysis of resurfacing operation, 6 optimization variables have been identified:

1. *Hourly Flow Rate in Direction* 1: Number of vehicle in the same direction with work zone.

2. *Hourly flow rate in Direction* 2: Number of vehicle in opposite direction against work zone.

3. *Average maintenance time per lane-km:* the required duration for maintenance for each lane per kilometer

4. *Work zone length:* the optimum length for work zone that decreases delay in traffic time and decrease accidents.

5. *Average work zone speed:* speed of vehicle at work zone.

6. *Average headway:* the time of the distance between two vehicles as shown in Fig. 4.

A fitness function is a particular type of objective function that prescribes the optimality of a solution (i.e., a chromosome) in genetic algorithms so that that particular chromosome is ranked against all the other chromosomes. Optimal chromosomes, or at least chromosomes which are more optimal, are allowed to breed and mix their datasets by any of several techniques, producing a new generation.

4.2. Multi-objective optimization algorithm

The objective of the work zone multi optimization problem is to minimize the total cost as in single optimization that explained before and minimize total duration for work zone activities. The objective function for work zone activities is expressed as per Eq (7):

$$\text{Minimize } C_T = C_M + C_U, \tag{7}$$

$$\text{Minimize } D_T = z_3 + z_4 L, \tag{8}$$

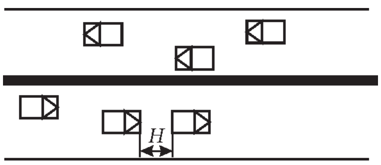

Fig. 4. Average headway (H)

where C_T – the total cost; C_M – the maintenance cost; C_U – the user cost; z_3 – setup time; z_4 – average maintenance time per lane-km; L – work zone length in km.

The same optimization variables of single-objective optimization are considered in multi-objective optimization. Pareto optimality is used to determine the set of optimal solutions. A solution is Pareto-optimal if no other solution improves one objective function without a simultaneous deterioration of at least one of the other objectives. A set of such solutions is called the Pareto-optimal front.

5. Numerical example

In order to demonstrate the use of the developed framework in optimization resurfacing operation of highways for an actual project example is considered. The example involves a highway (named El-Mehwer) with a length of 15 km that connects El-Giza Governorate to 6 October Governorate in Egypt. The values of the considered parameters are listed in Table 7. The boundaries of optimization parameters are listed in Table 8. Several experiments have been carried out to test the performance of the optimization module against different values of crossover threshold

Table 7. Example input parameters

Parameter	Value
Fixed cost for setting up a work zone, (Z_1)	80 L.E/Zone
Average additional maintenance cost per unit length (Z_2)	160 L.E/Lane.mm
Setup time (Z_3)	10 h/Zone
Value of user time (v)	12.7 L.E/veh.h
Speed on the original road (V_0)	80 km/h
Number of accidents per 100 million vehicle hours (n_a)	67 accident/100 mvh
Average cost per accident (v_a)	17.6 L.E/h

Table 8. Limits of optimization parameters

Parameter	Min value	Max value
Q_1	3 000 veh/h	5 000 veh/h
Q_2	3 000 veh/h	5 000 veh/h
Z_4	10 h/Lane.mm	20 hr/Lane.km
L	1 km	15 km
V	10 km/h	15 km/h
H	2 sec	10 sec

(CO), mutation threshold (m), and number of generations (G). Table 9 lists the outputs, obtained from the sensitivity analysis. Fig. 5 shows the change in Total cost at different mutation and crossover thresholds. The results reveal that solutions are too sensitive to both crossover and mutation values. For this road, best solutions for minimum cost are obtained at CO = 0.5 and m = 0.1.

The same example is solved to demonstrate the use of multi-objective algorithm. Several experiments have been carried out to test the performance of optimization with respect to project total cost (LE) and project duration (Dur.) in months against different values of crossover threshold (CO), mutation threshold (m), considering population size of 30 chromosomes as per Fig. 6.

Table 9. Values of optimization parameters for optimum solution (CO = 0.5 and $m = 0.1$)

Variable	Q_1	Q_2	Z_4	L	V	H
# Generation 100	50.12	51.27	10.21	4.84	14.97	2.01
# Generation 500	50.09	50.03	10.00	4.77	12.70	2.01
# Generation 1000	50.06	50.03	10.00	4.76	12.70	2.01

6. Summary

Repairing highway project is one of the complex projects that are characterized by repetitive operations, difficult construction environment, and different construction tools. Such characteristics lead to uncertainties with respect to estimated duration and repairing cost. This paper presented a framework that is used for planning of highways resurfacing using computer simulation and optimization. The proposed framework is capable to plan required repairing of highways. It aids in the selection of work zone length that achieves minimum total cost and total duration. The simulation module is implemented using the Microsoft Visual basic 6.0 programming language and it utilizes STROBOSCOPE (general purpose simulation

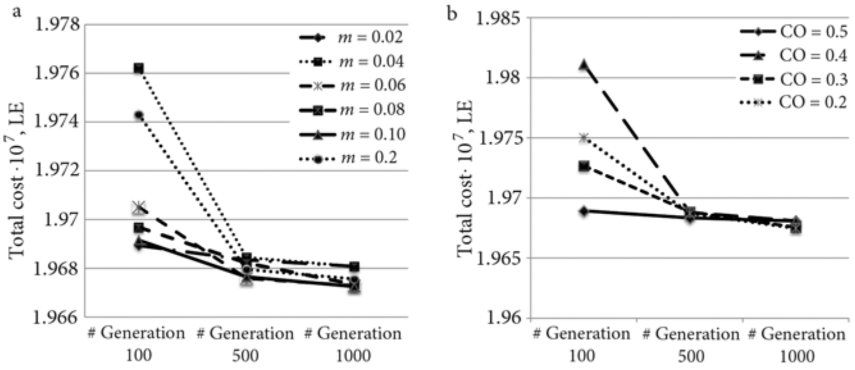

Fig. 5. Total Cost vs. No. of generations: a – different mutation thresholds (CO = 0.5); b – different crossover thresholds ($m = 0.02$)

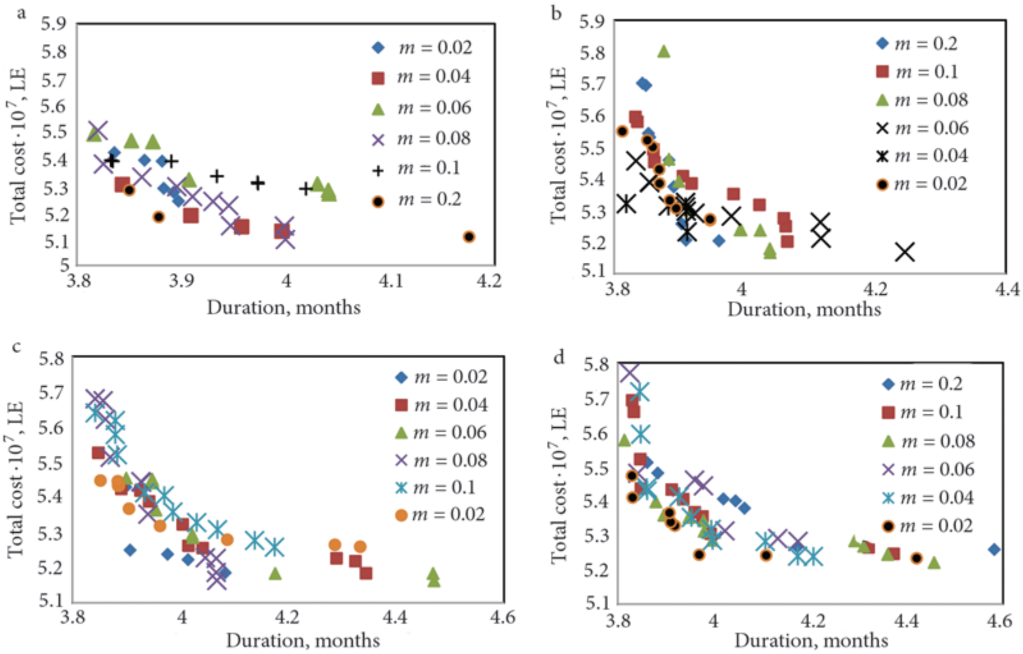

Fig. 6. Sensitivity analysis results: a – CO = 0.6; b – CO = 0.4; c – CO = 0.2; d – CO = 0.1

language) as simulation engine. Simulation module sends the estimated duration for each zone to calculate the total duration and total cost for repairing highway operation. The total cost is calculated by summing up the direct cost of resurfacing, indirect/overheads cost, and the cost of the impact of work zone on road, which are moving delay cost, queuing delay, and accident cost. Two genetic algorithms optimization were considered; single-objective optimization and multi-objective optimization. To demonstrate the functionality of the proposed framework, a numerical example was worked out. Sensitivity analysis was performed to test the performance of optimization with respect to project total cost (LE) and project duration (Dur.) in months against different values of crossover threshold (CO ranges from 0.1 to 0.6), mutation threshold (m ranges from 0.02 to 0.2), considering population size of 30 chromosomes.

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