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WORK ZONE SCHEDULING PROBLEM IN THE URBAN TRAFFIC NETWORKS

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Abstract: A significant part of highway and street congestion is produced by work zones. Depending on the type of construction and/or rehabilitation activity, street capacity could be significantly decreased, or the street could be completely closed. The work zone generates traffic delays in the street where maintenance is performed. Additionally, the work zone generates additional traffic on the neighboring streets, since many drivers change their routes. There are numerous possible work zone schedules. The total travel time of all network users highly depends on the chosen work zones schedule. Work zones scheduling problem has a natural nested structure that requires to be modeled as a bi-level problem. We considered the bi-level work zones scheduling problem. The objective function in the upper level, which we try to minimize, represents the total travel time of all network users. Relations in the lower level, help us to compute User Equilibrium flows. The proposed solution to the problem is based on the combination of Integer Programming and a heuristic traffic assignment algorithm. The output of the developed model consists of the start time of each work zone. The Sioux Falls benchmark network is used to illustrate the proposed procedures and the achieved performances.

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1. Introduction

Traffic congestion has been a serious problem in many cities in the world. The citizens of many big cities, now, waste between 30 and 60 minutes when commuting to work. Increasing road network capacities to satisfy growing travel demand is environmentally damaging and enormously costly. City planners and traffic engineers have initiated different demand management strategies in an attempt to lighten the increasing traffic congestion (park-and-ride, high occupancy vehicle lanes (HOV), high occupancy toll lanes (HOT), congestion pricing, etc.).

A significant part of highway and street congestion is produced by work zones. According to Kim et al. (2008), nearly one-quarter of all nonrecurring congestion on freeways in the US was caused by various work zone activities. The aging highway and street infrastructure in many cities raise the number of construction and/or rehabilitation work zones. Some streets are milled and overlaid. City Authorities also perform various activities to keep in good conditions drinking water and sanitation services in. In some cases, authorities perform a complete reconstruction of the street. This reconstruction could consist of subgrade repair, new asphalt pavement, and new curbs and gutters. There is also a constant need for the repair and maintenance of networks of gas, sewer, water, and electricity services. Depending on the type of construction and/or rehabilitation activity, street capacity could be significantly decreased, or the street could be completely closed. Various activities at work zones disturb traffic flows. Additionally, they significantly decrease safety for drivers, pedestrians, and work-zone workers. Work zone also generates traffic delay in the street where maintenance is performed. Additionally, the work zone generates additional traffic on the neighboring streets, and many other streets, since many drivers change their routes. In other words, work zones have network-wide traffic impacts by increasing travel times, level of traffic congestion, and the number of traffic accidents. In larger cities, there is usually a great number of work zones in different locations.

The majority of the available work-zones software packages primarily evaluate queuing delays at the local work-zone construction streets. In other words, these packages estimate work zones' impact on the streets in the neighborhood. We do believe that work zones gave a much broader impact on traffic conditions. To minimize the negative impacts of work zones, traffic authorities should coordinate work zone activities. The coordination could be performed within a specific corridor, urban traffic network, or wider region. In this paper, we study the work zone scheduling problem. Work zones could be scheduled to start at the same time, or at various times. They could overlap (in time), less or more. There are numerous possible work zone schedules. Network users become relatively fast and well-informed with the new network topology caused by the specific work zone schedule. Consequently, they search for the most convenient routes through the network, creating user equilibrium traffic conditions in the network. In other words, every considered work zone schedule generates a new network configuration and corresponding user equilibrium traffic conditions. The total travel time of all network users highly depends on the chosen work zones schedule. The primary objective of this paper is to propose a new methodology that facilitates city authorities to schedule several work zone activities in a way that minimizes network users' disruptions. In this paper, we look for the work zone schedule that minimizes the total travel time of all users, caused by work zones. We formulate the work zones scheduling problem as a bi-level program.

In years to come, city authorities and transportation planners will face the work zone scheduling problem more. In addition to better-scheduled construction and/or rehabilitation activities, traffic authorities will be also forced to provide better traffic management plans. Successfully planned and implemented work zone scheduling can result in a minimal decrease in the total travel time of network users, as well as a minimal decrease in the total number of traffic accidents.

The following are contributions of this paper: (a) we offered the mathematical formulation of the work zones scheduling problem; (b) we treated formulated problem as a bi-level program; (c) we solved the considered problem by the combination of CPLEX and the incremental algorithm for traffic assignment; (d) we tested proposed approach on the Sioux Falls benchmark network.

This paper is organized as follows. Section 2 contains a literature brief review. A statement of the problem is given in Section 3. The proposed solution to the problem is described in Section 4. Section 5 contains experimental evaluation. Conclusions and recommendations for future research are given in Section 6.

2. Literature review

Many authors studied the work zone scheduling problem in the last few decades. We offer a very brief review of the research done.

Wei and Schonfeld (1993, 1994) developed a multi-period network design problem model for the dynamic investment problem. The authors proposed the branch-and-bound algorithm to determine the best project combinations and schedules. Additionally, an artificial neural network model was used to estimate multi-period user costs.

Chien et al. (2002) analyzed work zones on two-lane two-way highways. The authors proposed a numerical method to optimize work-zone scheduling and traffic control in cases when one lane at a time is closed. The objective function that was minimized represented the total costs (maintenance, labor/equipment idle, and user-delay costs).

Lee (2009) proposed a work zone scheduling model based on the combination of simulation and Ant Colony Optimization (ACO). In the proposed model, traffic delay caused by work zones is estimated by a simulation technique. The near-optimal work zone schedule is generated by the ACO technique. The developed model is applied to schedule a sewer system construction project in a city. Lee (2009) showed that the developed model generates 11.1% lower traffic delay that the project planner.

Hong Zheng et al. (2014) proposed the neighborhood search algorithm to solve the work-zone sequencing problem. The authors also proposed a method to estimate network-wide traffic delay. They did not perform User Equilibrium runs in the whole traffic network. In order to estimate traffic delays caused by work zones, the authors analyzed the drivers' rerouting among a set of alternative routes. They applied a *k*-shortest path algorithm to identify a set of alternative routes for each work zone link. The proposed approach was tested in a case study on a real-world Guam network.

Chien and Tang (2014) considered highway work zone scheduling problem. They developed a model that optimizes work zone lengths and schedules. The objective function, for a road maintenance project that they considered, consisted of the cost of maintenance, cost of stopping maintenance work road user cost, delay cost, vehicle operating cost, and accident cost. The search for the optimal solution is based on a Genetic Algorithm.

Pilvar (2015) formulated the street works optimization problem as a bi-level optimization programming problem. The higher level problem is associated with minimizing the cost of traffic delays, and the cost of performing street works. By a secondary objective function, Pilvar (2015) tried to capture the non-monetized disruptive effects of work zones ("accessibility degradation", "connectivity degradation", etc.)

Bhutani et al. (2016) studied the impact of mass rapid transit system construction work zones on the traffic environment. The authors studied the traffic flow characteristics, and fuel consumption at the work zone location. They also estimated economic loss due to the increased fuel consumption and loss of travel time in a work zone. The analysis is performed based on VisSim software.

Du et al. (2017) developed a hybrid machine-learning model to predict traffic delays within the work zone. The hybrid model is based on an artificial neural network (ANN) and a support vector machine (SVM). The proposed model predicts delays subject to road geometry, number of lane closures, and work zone duration.

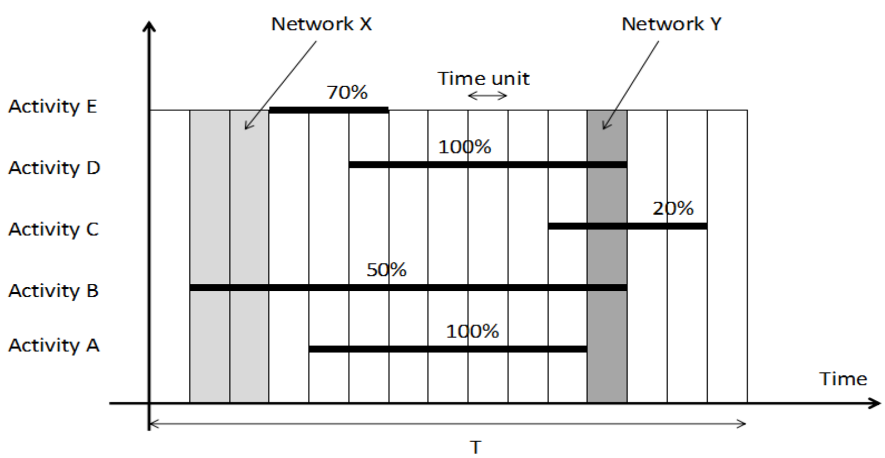
There are also many work-zone software packages (for example, QuickZone (Federal Highway Administration, 2004)). These packages primarily estimate traffic delays on work-zone streets.

3. Statement of the problem

We assume in this paper that we know in advance the total number of activities to be performed (reconstruction, repair, rehabilitation, …), as well as the duration of each activity. We do not analyze in this paper unplanned activities caused by hurricanes, earthquakes, floods, etc. In some cases, we can perform the planned construction and/or rehabilitation activity if we close the street completely. In some other cases, it is possible, for example, to close only one traffic lane, and perform work in other lanes later, during some other time periods, etc.

Every planned work zone is characterized by the following: (a) link on which construction and/or rehabilitation activities happen; (b) planned activity duration; (c) decrease in link capacity (link closure is represented by the degradation in link capacity that is equal to 100%). We assume that all planned activities must start and finish within the given time period *T* (Figure 1). The figure shows one possible Gantt chart - schedule (the start and end dates) of the planned activities *A*, *B*, *C*, *D*, and *E*, as well as their duration.

Figure 1. Gantt chart - schedule (the start and end dates) of the planned activities A, B, C, D, and E



The horizontal axis in Figure 1 represents time. Network topology is changed by starting any new activity. For example, the original traffic network (without any work zone) is transformed into network *X* by performing activity *B* (by closing, partially or completely, the link on which activity *B* is performed). Network *Y* is characterized by closing, partially or completely, the links on which activities *B*, *C*, and *D* are performed (Figure 1). The work zone schedule is defined by determining the beginning of each planned activity. Work zones force drivers to change their usual paths when traveling through the network.

We describe transportation networks by their set of nodes, set of links, link orientation, node connections, and link performance functions. These elements comprise transportation supply. Transportation demand is described by the Origin-Destination matrix. In this paper, we assume that the work zone activities force some drivers to change their usual routes. We have to answer the following questions: how network users will be distributed through the transportation network in the case of any specific work zone schedule? Network users could be distributed in many different ways through the network. The user equilibrium (UE), and system optimal (SO) represent two crucial traffic assignment models that have been created to solve the traffic assignment problem (Sheffi (1985), Teodorović and Janić (2022). In this paper, we search for the user equilibrium flows, during the work zone activities.

Let us introduce the following notation:

$G = (N, A)$ - transportation network

N - set of network nodes

A - set of network links

R - set of origin nodes

S - set of destinations nodes

P_{rs} - set of all paths between node *r* and node *s*

$r \in R$ - origin

$s \in S$ - destination

$p \in P_{rs}$ - path leading from node *r* to node *s*

q_{rs} - total number of travelers from node *r* to node *s*

x_{ai} - flow along link a on the i-th day

f_p^{rsi} - flow along path p that leads from node *r* to node *s* on the i-th day

t_p^{rsi} - travel time along path p that leads from node *r* to node *s* on the i-th day

$t_{ai} = t_{ai}(x_{ai})$ - travel time along link $a \in A$ on the i-th day

$$\delta_{ap} = \begin{cases} 1, \text{when link } a \text{ belongs to the path } p \\ 0, \qquad otherwise \end{cases}$$

n – considered period within all rehabilitations must be finished (in days)

m – number of the daily rehabilitation schedules

c – the number of the rehabilitation activities

n_v – duration of the rehabilitation activity v (in days)

$$w_{vk} = \begin{cases} 1, \text{if the rehabilitation activity } v \text{ is included in the daily rehabilitation schedule } k \\ 0, \qquad \text{otherwise} \end{cases}$$

$$y_{ik} = \begin{cases} 1, \text{if the } i\text{th day has the daily rehabilitation schedule } k \\ 0, \qquad \text{otherwise} \end{cases}$$

$$z_{vi} = \begin{cases} 1, \text{if the rehabilitation activity } v \text{ starts at the day } i \\ 0, \qquad \text{otherwise} \end{cases}$$

City traffic authorities, traffic engineers, and planners have to decide about the best work zone schedule. City traffic authority could be treated as a player that leads the game (leader). The leader (city traffic authority) moves first, trying to minimize the defined objective function. Network users represent the second player (follower). The second player responds in a rational way to the first player's decision. The objective and/or constraints of the follower (network users) are influenced by the leader's (traffic authorities) decisions. In other words, once the traffic authorities close some of the streets and start rehabilitation, some of the network users change their usual routes and create new traffic assignment.

Traffic authorities influence the behavior of network users, but do not have full control of the drivers. The new traffic flows are created by drivers' own logic in a new situation. Obviously, the decisions and actions of traffic authorities influence the drivers' route choices and vice-versa. This decision-making situation is characterized by a hierarchical structure. In other words, a lower-level (follower) optimization problem exists as a constraint of the upper-level (leader) problem.

We model the problem, considered in this paper, as a bi-level optimization problem. The objective function (that represents the total travel time of all network users) is placed in the upper level while trying to solve the user equilibrium traffic assignment problem in the lower level. The bi-level programming problem (Chandler and Norton (1977), Fortuny-Amat and McCarl (1981), Aiyoshi and Shimizu (1981, 1984), LeBlanc and D.E. Boyce (1986), Anandalingam and Apprey (1991), Ben-Ayed et al. (1988, 1992), Bard (1998), Bagloee and Sarvi (2018)) represents a static version of the non-cooperative, two-person game introduced by Von Stackelberg (1952). Bi-level programs include a leader and a follower that operate in a hierarchical manner. In bi-level programs, the evaluation of a single upper-level solution demands discovering its corresponding optimal lower-level solution.

The bi-level work zones scheduling problem for the *t*-th day of the schedule *s* reads:

Upper level:

Minimize

$$F_1 = \sum_{i=1}^{n} \sum_{a \in A} x_{ai} \cdot t_{ai}(x_{ai}) \quad (1)$$

Lower level:

Minimize

$$F_{2i} = \sum_{a \in A} \int_0^{x_{ai}} t_{ai}(x_{ai})\, dx \qquad \forall\, i = 1, \ldots, n \quad (2)$$

subject to

$$\sum_{p \in P_{rs}} f_p^{rsi} = q_{rs} \qquad \forall\, r \in N, s \in N, i = 1, \ldots, n \quad (3)$$

$$x_{ai} = \sum_{r \in R} \sum_{s \in S} \sum_{p \in P_{rs}} f_p^{rsi}\, \delta_{ap} \qquad \forall\, a \in A, i = 1, \ldots, n \quad (4)$$

$$\sum_{k=1}^{m} y_{ik} = 1 \qquad \forall\, i = 1, \cdots, n \quad (5)$$

$$\sum_{i=1}^{n-n_v+1} z_{vi} = 1 \qquad \forall\, v = 1, \cdots, c \quad (6)$$

$$n_v \cdot z_{vi} \le \sum_{j=i}^{i+n_v} \sum_{k=1}^{m} w_{vk} \cdot y_{jk} \qquad \forall\, v = 1, \cdots, c; i = 1, \cdots, n - n_v + 1 \quad (7)$$

$$f_p^{rsi} \ge 0 \qquad \forall\, r \in N, s \in N, p \in P_{rs}, i \quad (8)$$

$$x_{ai} \ge 0 \qquad \forall\, a \in A, i = 1, \ldots, n \quad (9)$$

$$y_{ik} \in \{0, 1\} \qquad \forall\, i = 1, \ldots, n, k = 1, \ldots, m \quad (10)$$

$$z_{vi} \in \{0, 1\} \qquad \forall\, v, i = 1, \ldots, n \quad (11)$$

The objective function F_1 in the upper level, which we try to minimize, represents the total travel time of all network users. At the lower level, we must determine the schedules of daily rehabilitations, and for each day to perform the traffic assignment. Consequently, we have *n* objective functions (2) that should be minimized.

Constraint (3) guarantees that the whole flow from node *r* to node *s* is assigned to the available paths. Link flows are expressed as a function of path flows (constraint (4)). Constraint (5) states that one daily rehabilitation schedule must be assigned to each day. Constraints (6) and (7) guarantee that each activity will begin and end within the observed time period. Constraints (8) - (11) define decision variables.

The work zones scheduling problem belongs to the class of difficult combinatorial optimization problems. When searching for the optimal work zone schedule, we try to minimize the total travel time of all network users. This could create huge computational difficulties since it is necessary to solve the user equilibrium problem many times every day within a specific work zone schedule. In some cases, additional constraints could appear (scheduling precedence requirement, etc.). This could further increase the problem's complexity.

4. Proposed solution to the problem

To solve the problem effectively, we propose the following two-step approach:

- For all possible daily rehabilitation activities schedules find user equilibrium and calculate the total travel time for all network users.
- Determine the schedules for rehabilitation activities in such a way as to minimize the total travel times of all network users.

Within the first step, we must evaluate the total travel time for each rehabilitation schedule. For that purpose, it should be used one of the already known algorithms for discovering user equilibrium. To solve the case study considered in this paper, we have used the incremental traffic assignment algorithm that has the following steps (Sheffi (1985), Teodorović and Janić, 2022):

Step 0: Split each origin-destination flow into *I* equal shares, i.e.:

$$q_{rs}^{i} = \frac{q_{rs}}{I} \tag{12}$$

Set iteration counter $i = 1$ and $x_a^0 = 0, \forall\, a$.

Step 1: Set $t_a^i = t_a\left(x_a^{i-1}\right), \forall a$.

Step 2: Make all-or-nothing assignment of shares q_{rs}^{i}, based on travel times $\{t_a^i\}$. Get a set of link

flows $\{y_a^i\}$.

Step 3: Set $\{x_a^i = x_a^{i-1} + y_a^i\}$, $\forall a$.

Step 4: If $i = I$, finish the algorithm. Otherwise, set $i = i + 1$, and return to step 1.

When the traffic assignment is determined, it is necessary to calculate the total travel time of all network users. Let us denote by T_k the total travel time of all network users for rehabilitation schedule *k* (*k* = 1, …, *m*). The values of the variables y_{ik} and z_{vi}, that define rehabilitation schedules, are found after solving the following program:

Minimize

$$F = \sum_{i=1}^{n} \sum_{k=1}^{m} T_k \cdot y_{ik} \tag{13}$$

s.t.

$$\sum_{k=1}^{m} y_{ik} = 1 \qquad \forall\, i = 1, \cdots, n \tag{14}$$

$$\sum_{i=1}^{n-n_s+1} z_{si} = 1 \qquad \forall\, s = 1, \cdots, p \tag{15}$$

$$n_v \cdot z_{vi} \leq \sum_{j=i}^{i+n_v} \sum_{k=1}^{m} w_{vk} \cdot y_{jk} \qquad \forall\, v = 1, \cdots, c;\ i = 1, \cdots, n - n_v + 1 \tag{16}$$

$$y_{ik} = \{0, 1\} \qquad \forall\, i = 1, \cdots, n;\ k = 1, \cdots, m \tag{17}$$

$$z_{vi} = \{0, 1\} \qquad \forall\, v = 1, \cdots, c;\ i = 1, \cdots, n - n_v + 1 \tag{18}$$

The objective function (13) represents the total travel time, and it should be minimized. Generally, this mathematical formulation has the same as the first objective in the previous formulation. Also, the constraints (14), (15) (16), (17), and (18) are the same as the constraints (5), (6), (7), (10), and (11).

5. Experimental evaluation

We tested the proposed approach on the Sioux Falls benchmark network (Figure 2). The network has 24 nodes and 76 links. All tests were solved by CPLEX 20.1 at the computer with the following characteristics: 11th Gen Intel(R) Core(TM) i7-11800H @ 2.30GHz, 16 GB of installed RAM, and Windows 11 operating system.

We considered two different traffic scenarios. The observation periods in these scenarios were 15 and 30 days, respectively. We varied the number of planned activities, from 2 to 10, within the observed traffic scenarios. Additionally, we considered shorter (case 1) and longer (case 2) duration of activities within each scenario. Details related to the characteristics of the rehabilitation activities are given in Table 1. The streets on which the rehabilitation activity should be done are given in the second column of Table 1. The duration of rehabilitation activities (in days) is given in columns 3 and 4 respectively. We assumed that all the links on which rehabilitation is being carried out are closed to traffic.

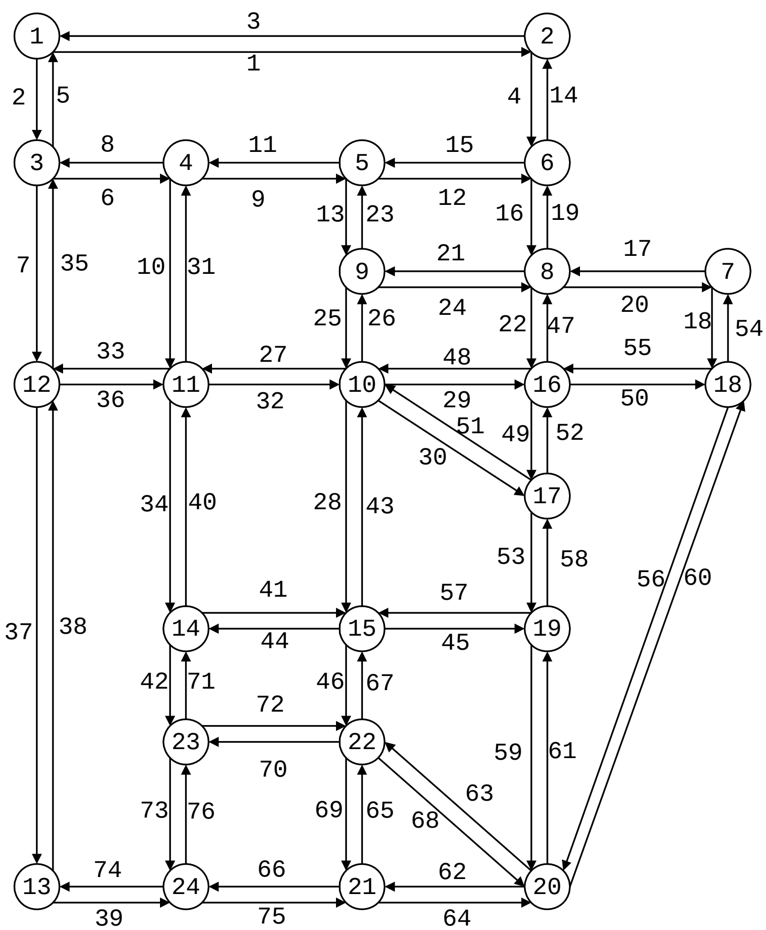
Before finding the optimal schedules for the considered scenarios, the values of total travel times of all network users were determined in cases where no activity is performed on the observed network. These values were determined by discovering user equilibrium conditions. The total travel time in the first scenario, with the period of 15 days, is 11588.16 minutes. In the second scenario, with the period of 30 days, the total travel time equals 23176.2 minutes.

Table 1. Characteristics of the rehabilitation activities

Rehabilitation activity	Link number	Case 1 Duration of shorter activities (days)	Case 2 Duration of longer activities (days)
1	25	2	8
2	24	3	5
3	42	4	7
4	27	2	4
5	8	4	8
6	10	1	9
7	66	2	10
8	44	3	12
9	45	2	8
10	56	3	10

Table 2 shows the obtained results for Scenario #1. We notice, (as could be expected intuitively) that more activities cause a longer total travel time. For example, if we have only two activities (the first and second activity should be finished) the increase in total travel time is $\frac{12403.88-11588.16}{11588.16} \cdot 100\ \% = 7.04\ \%$, while for ten activities the increase in total travel time equals $\frac{15308.15-11588.16}{11588.16} \cdot 100\ \% = 32.1\ \%$. The increase is even more significant in the case when the duration of activities is longer. For example, when only two longer activities are performed, the increase in total travel time is $\frac{13741.33-11588.16}{11588.16} \cdot 100\ \% = 18.58\ \%$. The graphical illustration of the increase in total travel time is given in Figure 3. As can be seen, a significant increase in the number of activities that are performed simultaneously during the observed period can lead to very large values of the total travel time in the network. This small illustrative example points to the fact that due attention must be paid to the planning process of network construction and/or rehabilitation activities. Otherwise, the consequences for the functioning of the city and the level of service provided to traffic network users can be extremely negative.

Figure 2. Sioux Falls Network

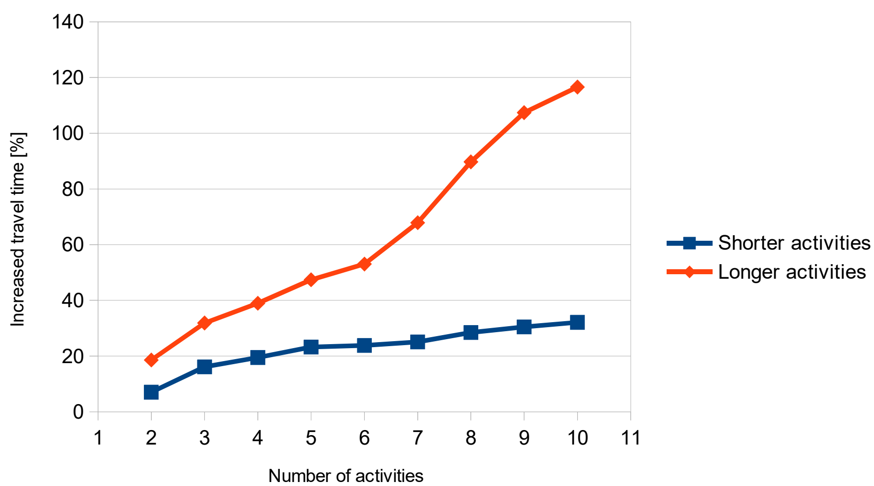


It is also very important to notice the difference in the required CPU time for solving the considered examples. We notice that CPU times are similar for the shorter and longer duration of activities. The second very important fact is that the examples with activities between 2 and 8 can be solved very fast, while the CPU time is significantly longer for 9 and 10 activities.

Table 2. The total travel times of all network users for the 15 day's period

Number of activities	Rehabilitation activities	Shorter activities		Longer activities	
		Total travel time [min]	CPU time [s]	Total travel time [min]	CPU time [s]
2	1, 2	12403.88	0.08	13741.33	0.11
3	1, 2, 3	13455.32	0.14	15278.65	0.09
4	1, 2, 3, 4	13846.90	0.31	16102.11	1.14
5	1, 2, 3, 4, 5	14281.52	2.63	17079.89	1.20
6	1, 2, 3, 4, 5, 6	14347.16	6.61	17733.60	3.80
7	1, 2, 3, 4, 5, 6, 7	14494.21	7.47	19455.97	7.66
8	1, 2, 3, 4, 5, 6, 7, 8	14886.67	13.52	21986.95	10.64
9	1, 2, 3, 4, 5, 6, 7, 8, 9	15117.35	332.53	24034.39	314.94
10	1, 2, 3, 4, 5, 6, 7, 8, 9, 10	15308.15	2025.75	25098.33	2735.67

Figure 3. Increased travel times when the period is 15 days (the scenario #1)

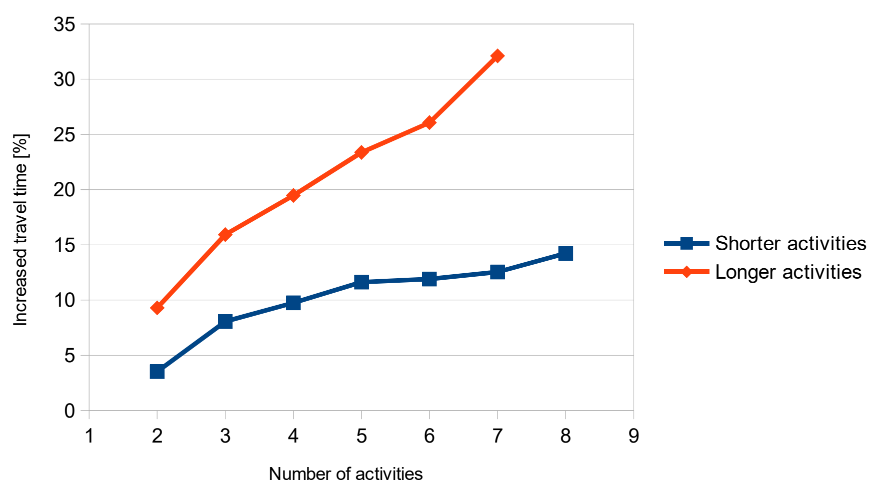


We also tried to solve the previous examples in the case of scenario #2, when the duration of the period is 30 days. In the case with shorter activities, we successfully solved the examples with eight or fewer rehabilitation activities, while in the case with longer activities we solved the examples with seven or fewer activities. The search for the solution, in the case of examples with more activities, has been stopped after a couple of hours. The obtained results are presented in Table 3. One can notice that, within 30 days scenario, the examples with longer activities need significantly more CPU time than the examples with shorter activities. The increase in travel time for the 30 days scenario is presented in Figure 4. Like in the case of scenario #1, the longer activities caused a bigger increase in the total travel time. The shorter period causes many activities in the network should be finished simultaneously. In such a situation, the increase in the total travel time is significant (Figure 3 and Figure 4).

Table 3. The total travel times of all network users for the 30 days' period (scenario #2)

Number of activities	Rehabilitation activities	Shorter activities		Longer activities	
		Total travel time [min]	CPU time [s]	Total travel time [min]	CPU time [s]
2	1, 2	23992.04	0.17	25329.49	0.24
3	1, 2, 3	25043.48	0.27	26866.81	1.83
4	1, 2, 3, 4	25435.06	3.19	27690.27	34.34
5	1, 2, 3, 4, 5	25869.68	12.02	28592.62	20.41
6	1, 2, 3, 4, 5, 6	25935.33	163.73	29217.85	5474.23
7	1, 2, 3, 4, 5, 6, 7	26082.37	130.44	30618.27	8043.16
8	1, 2, 3, 4, 5, 6, 7, 8	26474.84	285.58	-	-
9	1, 2, 3, 4, 5, 6, 7, 8, 9	-	-	-	-
10	1, 2, 3, 4, 5, 6, 7, 8, 9, 10	-	-	-	-

Figure 4. Increased travel time when the period is 30 days



6. Conclusions

In this paper, we studied the work zone scheduling problem. The considered problem is extremely important due to the fact that a considerable part of highway and street congestion is produced by work zones. Work zone generates traffic delay in the street where maintenance is performed, as well as on the neighboring streets since many drivers change their routes. The total travel time of all network users greatly depends on the chosen work zones schedule. We treated the work zone scheduling problem as a bi-level program. The objective function in the upper level, which we try to minimize, represents the total travel time of all network users. Relations in the lower level, help us to compute User Equilibrium flows. The solution approach developed in this paper is based on the combination of Integer Programming and a heuristic traffic assignment algorithm. The output of the developed model consists of the start time of each work zone. The Sioux Falls benchmark network is used to illustrate the proposed procedures and the achieved performances.

The numerical examples solved in this paper were of a relatively small dimensionality. At the same time, the problem studied is combinatorial by its nature. The optimal solution to the considered problem cannot be found in acceptable CPU time in the cases of big traffic networks. There is a combinatorial explosion of promising combinations of the decision variables that could be optimal. In future research, it would be extremely important to explore various approximate algorithms when solving work zone scheduling problems. Metaheuristics have become a very dominant approach in the last few decades, for solving hard combinatorial optimization problems. They are general-purpose techniques, and they efficiently explore the search space. The gained experience shows that the meta-heuristics are doing well in generating (near)-optimal solutions to difficult combinatorial optimization problems, in an acceptable computer time.

The main task of future research is the development of models based on various metaheuristic techniques and their testing on large networks.

It would be also challenging to develop more sophisticated models that take into account more negative aspects of work zones (increased travel times, increased number of stops, unexpected delays, greater travel costs, inconvenience to drivers and passengers, increased air pollution and noise levels, and increased number of traffic accidents).

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VREMENSKO RASPOREDJIVANJE RADOVA NA SAOBRAĆAJNIM MREŽAMA

Apstrakt: Saobraćajna zagušenja su u, značajnioj meri, uzrokovana radovima koji se obavljaju na saobraćajnim mrežama. U zavisnosti od tipa radova, kapacitet pojedinih saobraćajnica može da bude smanjen, ili saobraćajnica može u potpunosti da bude zatvorena za saobraćaj. Pored toga što dovode do povećanih vremena putovanja na saobraćajnicama u kojima se izvode radovi, aktivnosti održavanja utiču i na uslove odvijanja saobraćaja u susednim ulicama, obzirom da mnogi vozači menjaju svoje uobičajene rute. Postoji veoma veliki broj načina na koje planirani radovi mogu da budu rasporedjeni u vremenu. Ukupno vreme putovanja svih korisnika na mreži u značajnoj meri zavisi od izabranog vremenskoh rasporeda radova koje je potrebno obaviti. Problem vremenskog rasporedjivanja radova na mreži ima takvu prirodu i strukturu da zahteva da bude razmatran kao problem bi-level programiranja. Kriterijumsku funkciju na gornjem nivou, koju smo težili da minimiziramo, predstavlja ukupno vreme putovanja svih korisnika na mreži. Relacije na donjem nivou omogućavaju izračunavanje vrednosti intenziteta tokova i vremena putovanja u uslovima korisničkog ekvilibrijuma. Predloženi način rešavanja problema zasnovan je na kombinaciji Celobrojnog programiranja i heurističkog algoritma za pronalaženje korisničkog ekvilibrijuma. Izlazne rezultate predstavljaju momenti započinjanja svake od planiranih aktivnosti održavanja. Predloženi model je testiran na primeru američkog grada Sioux Falls.

Ključne reči: Vremensko rasporedjivanje radova, raspodela saobraćaja na mreži, kombinatorna optimizacija, inkrementalni algoritam

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