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A Mathematical Model for Ballast Tamping Decision Making in Railway Tracks

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Abstract

Ballast tamping is considered as an important maintenance process for railway infrastructures and has a large influence on the capacity of any railway networks. But optimizing the plan of that process is a complex problem with a high cost. This paper discusses optimizing tamping operations on ballasted tracks to improve the track geometry and reduce the total maintenance cost. A mathematical model for this problem in the literature is improved here by including the restriction on the resources (tools, workers and budget) in the model and including constant/variable values for track possession cost and available resources. The optimal solutions obtained for all instances are found by using the global optimization. Besides, a numerical study is presented to test and evaluate the model performance. The results show that the proposed model can be adopted by the infrastructure manager (IM) to make suitable tamping scheduling decisions under normal or private conditions; however, the private conditions lead to an increase of the final cost compared to that of the normal ones.

Keywords: Ballast; Tamping; Track Possession; Decision Making; AMPL; CPLEX.

1. Introduction

Ballast tamping is considered to be an important maintenance operation for railway infrastructures and has a big influence on the capacity of railway tracks because of its private requests such as possessing a track for a long time, heavy equipment involved, planning difficulties, etc. [1]. Furthermore, tamping process is too expensive [2], therefore an optimal scheduling for this process is required to minimize the total cost as much as possible (Famurewa et al. 2015 [1]; Miwa 2002 [3]; Oh et al. 2006 [4]; Macke and Higuchi 2007 [5]; Andrade and Teixeira 2011 [6]; Heinicke et al. 2015 [7]).

In this paper, the problem of optimal planning of ballast tamping tasks on a railway track is presented, and the aim is to get the optimum plan for them minimizing the discounted total cost (DTC) in a given horizon. Some assumptions and considerations are explained as the following:

- The track in concern is composed by a series of sections of 200 m of length,

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- The track condition degradation for each section is determined by the increase of the standard deviation of the longitudinal level over wavelengths from 3 to 25 m as in Gustavsson (2015) [8]. Moreover, it is assumed that this degradation is a linear one over time,
- It is assumed that there is a linear relationship between the recovery of track section condition and the standard deviation of the longitudinal level of that section at the time of tamping,
- It is assumed that the tamping process is being performed at the end of each period,
- It is considered the DTC for the objective function and the constraints of the available workforce in the proposed model, and
- The concern model in this paper is carried out in AMPL [9] and solved by CPLEX (version 12.6.2.0) [10].

In literature, a lot of studies have been presented to obtain an optimal schedule of maintenance activities in railway systems by using several methods and techniques in operations research. Budai et al. (2006 and 2009) [11, 12] studied the preventive maintenance scheduling problem (PMSP) for railway infrastructures. In the first work, the authors solved that problem by using two heuristics and solved it in the second one by using genetic and memetic algorithms. Peng et al. (2011) [13] applied a heuristic solution approach which used local search and project swapping method to solve the railway track maintenance scheduling problem in order to minimize the total travel costs of the maintenance crews and the influence of maintenance projects on railway operation. Gustavsson et al. (2014) [14] provided the model of the opportunistic replacement problem to the scheduling problem of preventive maintenance with interval costs in order to plan maintenance actions over a finite horizon minimizing the costs for all maintenance intervals. Another study proposed a mathematical model for the PMSP under different (seasonal) values of the track possession cost in the planning horizon. Then the authors compared between the optimum schedules for fixed and seasonal possession costs for a set of maintenance activities, in order to analyze the impact of possession costs on the optimal plan of the PMSP (Daddow et al. 2016 [15]). Also, many other papers have studied the PMSP (Higgins 1998 [16]; Canto 2008 [17]; Moghaddam and Usher 2011 [18]; Liu et al. 2019 [19]; Kamel et al. 2020 [20]).

Other optimization models have been developed in the area of optimal scheduling of ballast tamping tasks in the railway infrastructures. Oyama and Miwa (2006) [21] developed an optimization model for the planning of tamping actions that includes two steps: 1) a transition model for predicting changes in the surface irregularities; and 2) a mathematical model for getting a suitable plan for those actions. In another research, Zhang et al. (2013) [22] studied the problem of scheduling of tamping operations on a regional railway network in the UK and used a genetic algorithm to obtain its solution. Another valuable work related to the area is carried out by Vale et al. (2012) [23] where the authors developed a model for scheduling the tamping actions to minimize the total number of these actions on the determined track in a given horizon. Then Gustavsson (2015) [8] upgraded that model by taking disaggregated constraints for the track layout influence and minimizing the total cost instead of the total number of tamping operations. Also, Wen et al. (2016) [2] extended the model in Vale et al. (2012) [23] by minimizing the net present cost of the objective function and considering the impact of previous tamping operation through the calculation of track condition recovery. Daddow et al. (2017) [24] extended the model in [8] by regarding the effect of unused life of early tamped parts and the available workforce constraints in their model. Besides, the authors compared between two scenarios of minimum and maximum limits of the available maintenance crews. Finally, Bakhtiary et al. (2020) [25] improved a model that is available in the literature taking into account that an opportunistic maintenance threshold as a main decision variable in the new model in order to minimize the total cost of track tamping activities.

The contribution of this paper is to extend the mathematical model in [8] through the following respects:

- Consider the limitation of resources (machines, manpower, budget, etc.) in the model's constraints, and
- Consider constant/varied values for the track possession cost and available workforce for the time periods in the planning horizon.

This extension aims to help the infrastructure manager (IM) to get an optimum schedule for tamping operations on the studied track in the planning horizon under variable circumstances.

The remainder of this paper is organized as follows. Section 2 presents the problem statement. In Section 3, the mathematical formulation of the studied problem is provided. The computational results are presented and analyzed in Section 4. Finally, Section 5 presents conclusions and suggestions for future research.

2. Problem Description

This paper discusses the problem of optimum planning of tamping tasks on ballasted tracks. As above mentioned, it is considered that the railway track consists of many sections of 200 m of length, the track condition for each section is defined by its standard deviation of the longitudinal level and the condition of track section has a linear degradation over time and not allowed to exceed a specific limit (i.e. track quality limit). Furthermore, the linear relationship for the recovery value is calculated as shown in Equation 1 based on the Office for Research and Experiments (ORE, 1988) [26]:

$$r_i^j = a.(\sigma_i^{j-1} + d_i) + b \tag{1}$$

Where,

a, b = Real parameters which are used to determine the recovery value,

d_i = Degradation rate of the longitudinal deviation for the section i,

r_i^j = Recovery of the longitudinal deviation after tamping process for the section i in the period j,

σ_i^{j-1} = Longitudinal deviation for the section i at the end of the period $j-1$, and

$\sigma_i^{j-1} + d_i$ = Longitudinal deviation for the section i at the time of tamping operation.

Besides, the Union Internationale des Chemin de Fer (UIC, 2008) [27] recommends that tamping operations begin and end on a straight alignment in order to consider the impact of track layout on the tamping plan, where the track layout considers two types of the track sections, which are: 1) straight alignments (S); and 2) curves (C). Figure 1 explains how this recommendation is applied through the calculations. In this figure, it is assumed that the curve section 3 and the straight section 9 require to tamping actions. So that, the tamping process will include the sections 2, 3, 4, 5 and 6 together which they represent all members of the smallest set (I_3) of successive sections such that $3 \in I_3$ and the first and last sections in I_3 are straight sections, while it will include the section 9 only because this section is a straight one.

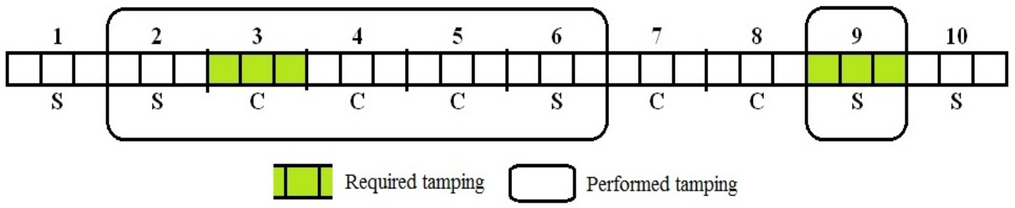

Figure 1. Track layout influence on tamping planning

It is worth noting that the available resources are limited (such as equipment, budget and maintenance crews), so it is assumed throughout this paper that the available workforce is restricted and does not exceed a certain threshold for each period in the planning horizon.

The aim of this paper is to obtain an optimum plan for the tamping tasks on the studied track minimizing the DTC in a finite horizon by considering constant/varied values for the track possession cost and the available workforce for the time periods of the planning horizon. The total maintenance cost contains two parts as follows:

- A unit ballast tamping cost for each section of the railway track, and
- A possession cost that is paid whenever any tamping job is being done on the railway track in that period.

3. Mathematical Formulation

A valuable advantage for Gustavsson's Model (GM) in [8] can be mentioned as the ability of considering track possession cost through the tamping scheduling procedure. This ability leads to result in cost savings by scheduling the tamping actions together as much as possible in the same period. But similar to any other model, that model has some weaknesses which one of them can be indicated that it does not consider the available workforce constraints in the model. Therefore, it may give an impractical plan for tamping operations for the studied track (for example, the total number of planned tamping actions in some periods more than the available workforce for the IM). Based on this weakness, GM has been improved in this paper in such a way that the available workforce constraints are involved in the model in order to obtain more practical solution for the studied problem. Besides, the model in this paper presents two benefits which are as follows:

- Possibility to consider varied available workforce values through every time period independently, and
- Possibility to consider different track possession cost values for every time period independently too.

Both benefits are very helpful for the IM to plan the tamping works based on his available circumstances in the studied area. However, the importance of these two benefits is shown in Section 4.2.

For this purpose, the relevant sets, parameters, decision variables, objective function, constraints and flowchart of the proposed model are presented below.

3.1. Sets and Parameters

The sets and parameters of the developed model in this paper are given as follows:

N = Set of considered track sections,

T = Set of time periods in the planning horizon,

$I_i \subseteq N$ = Smallest set - for each section $i \in N$ - of sequential indices of railway track section such that $i \in I_i$ and the first and last sections in I_i are straight alignments, while if the section i is a straight alignment then $I_i = \{i\}$,

mc = Unit ballast tamping cost,

pc^j = Unit possession cost for the period j,

r = Discount rate (%),

M = Adequately large number used in the big-M constraints of the problem,

d_i = Degradation rate of the longitudinal deviation for the track section i (mm/90 day),

$\sigma_i^{\max}$ = Maximum value of the longitudinal deviation for the section i based on the maximum allowable speed of the vehicle (mm),

σ_i^{init} = Longitudinal deviation for the section i at $j = 0$ (mm),

$a \& b$ = Real parameters to calculate the condition recovery, and

A^j = Maximum possible number of sections for tamping in the period $j \in T$.

3.2. Decision Variables

The decision variables are given as follows:

x_i^j = Binary decision variable that determines whether tamping process is assigned to the section $i \in N$ at the period $j \in T$ ($x_i^j = 1$) or not ($x_i^j = 0$),

z^j = Binary decision variable that indicates whether the track is used for tamping tasks at the period $j \in T$ ($z^j = 1$) or not ($z^j = 0$),

σ_i^j = Decision variable that calculates the longitudinal deviation for the track section $i \in N$ at the end of period $j \in T$ (mm),

r_i^j = Decision variable that determines the longitudinal deviation's recovery after tamping operation for the section $i \in N$ at the period $j \in T$ (mm), and

q_i^j = Decision variable that is used here to transfer the model from non-linear into linear one as in Vale et al. (2012) [23]. It equals to ($x_i^j . r_i^j$); where it takes the value of r_i^j when $x_i^j = 1$, and zero when $x_i^j = 0$ (mm).

3.3. Objective Function and Constraints

The objective function of the model is given as follows:

$$min \sum_{j \in T} \left[\left(\sum_{i \in N} mc.x_i^j + pc^j . z^j \right) . \left(\frac{1}{(1+r)^{0.25}} \right)^j \right] \tag{2}$$

Subject to the following constraints:

$$\sigma_i^j = \sigma_i^{j-1} + d_i - q_i^j \qquad i \in N,\ j \in T,\ j > 0 \tag{3}$$

$$q_i^j \le M.x_i^j \qquad i \in N,\ j \in T \tag{4}$$

$$0 \le r_i^j - q_i^j \le M.(1 - x_i^j) \qquad i \in N,\ j \in T \tag{5}$$

$$r_i^j = a.(\sigma_i^{j-1} + d_i) + b \qquad i \in N,\ j \in T,\ j > 0 \tag{6}$$

$$\sigma_i^{j-1} + d_i \le \sigma_i^{\max} \qquad i \in N,\ j \in T,\ j > 0 \tag{7}$$

$$\sigma_i^0 = \sigma_i^{init} \qquad i \in N \tag{8}$$

$$x_k^j \ge x_i^j \qquad k \in I_i,\ i \in N,\ j \in T \tag{9}$$

$$x_i^j \le z^j \qquad i \in N,\ j \in T \tag{10}$$

$$\sum_{i \in N} x_i^j \le A^j \qquad j \in T \tag{11}$$

$$x_i^j, z^j \in \{0,1\} \qquad i \in N,\ j \in T \tag{12}$$

$$\sigma_i^j, q_i^j, r_i^j \ge 0 \qquad i \in N,\ j \in T \tag{13}$$

Equation 2 defines the objective function which minimizes the DTC in the given horizon. The longitudinal deviation value for the section *i* at the end of period *j* is determined by Equation 3, where if there is a tamping action at the period *j* then that value is decreased by r_i^j . The value of q_i^j is determined through Equations 4 and 5. If $x_i^j = 0$ (i.e. no tamping for the section *i* in the period *j*) then q_i^j is set to 0 by Equation 4, otherwise q_i^j is set to r_i^j by Equation 5. The longitudinal deviation's recovery for the section *i* at the period *j* is calculated by Equation 6 which depends on the value of that deviation at the time of tamping. Equation 7 determines the maximum allowable value of the longitudinal deviation's growth for the section *i* and Equation 8 gives the initial value for that deviation when $j = 0$. Equation 9 ensures that any tamping operation will begin and end on a straight alignment and Equation 10 guarantees that the possession cost is considered every period in which any tamping process is being planned. The total number of tamping operations which can be planned in the period *j* and cannot be exceeded the value of A^j is ensured by Equation 11. Finally, the problem variables are defined by Equations 12 and 13.

3.4. Flowchart of the Model

The flowchart of the proposed model is shown in Figure 2. The first step involves determination of the related sets, parameters and decision variables. The second step entails formulation of the objective function as shown in Equation 2. The third step deals with formulation of the constraints, which are explained above. The fourth step includes performance of the suggested model in AMPL. The model described above has a linear objective function and linear constraints. Therefore, the model is treated as a mixed integer linear program (MILP). In the fifth step, the required data is determined as presented in the next section. The MILP model is solved by using CPLEX in the sixth step. The last step involves analysis of results as shown in Section 4.2.

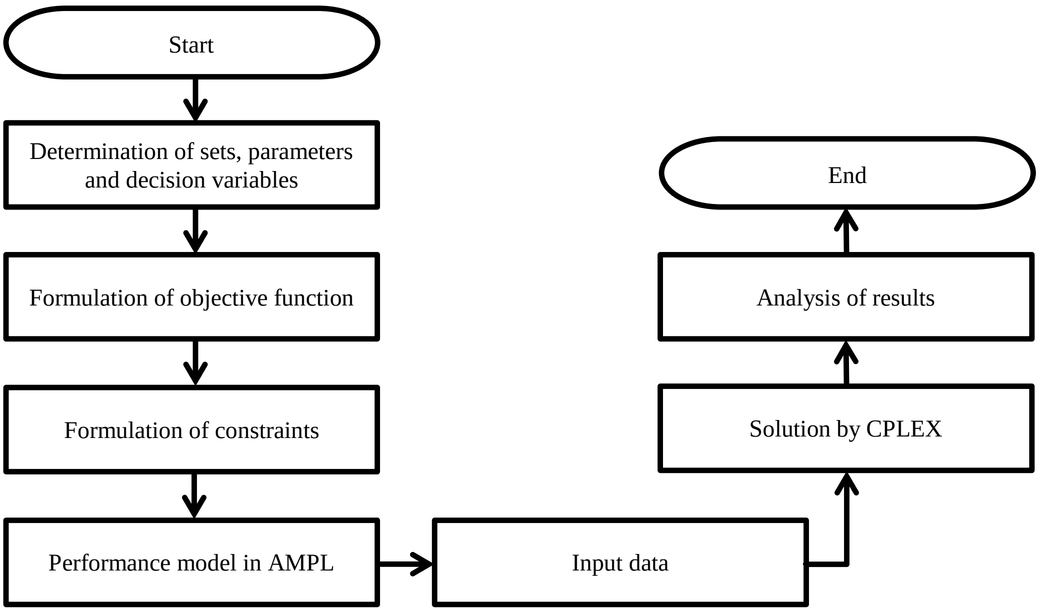

Figure 2. Framework of the planning model

4. Computational Results

4.1. The Included Data

It is adopted the following data for the calculations:

- The total number of track sections equals to 180 with length of 200 m,
- The planning horizon is 2 years and corresponds to eight time periods of 90 days,
- The parameters *a* and *b* equal to 0.4257 and -0.153, respectively as in Vale et al. (2012) [23],
- The unit ballast tamping cost mc =1, the available workforce A^j = 65 $\forall j \in T$, the possession cost $pc^j = 10$ $\forall j \in T$ a and the discount rate r = 4.5%,
- The track layout with *S* and *C* sections is shown in Figure 3. In this figure, the number of curve sections (*C*) equals to 87 which represents 48.33 % of the total considered track sections,
- The degradation rate for track sections (mm/day) is presented in Figure 4. It can be seen in this figure that the values are mostly varied between 0.0005 and 0.0025 mm/day,
- The initial condition for each section of the track (mm) is presented in Figure 5. Obviously, the studied truck has a good geometrical quality where most of values are less than 1.5 mm, and
- It is considered that the maximum train speed changes between 160 and 220 km/h, hence the track quality limit for all sections equals to 1.9 mm based on EN13848-5 (CEN, 2008) [28] as shown in Figure 5.

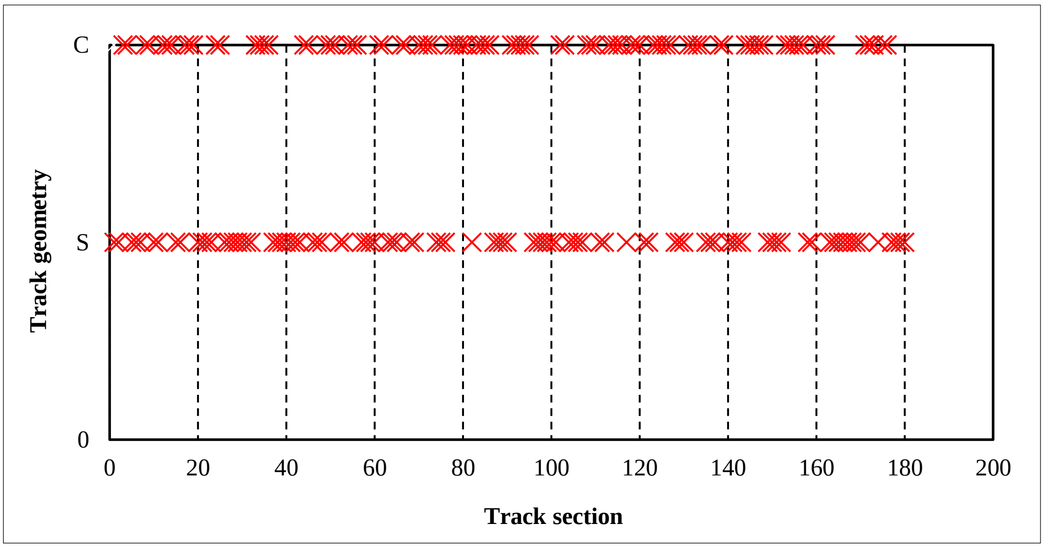

Figure 3. The track layout

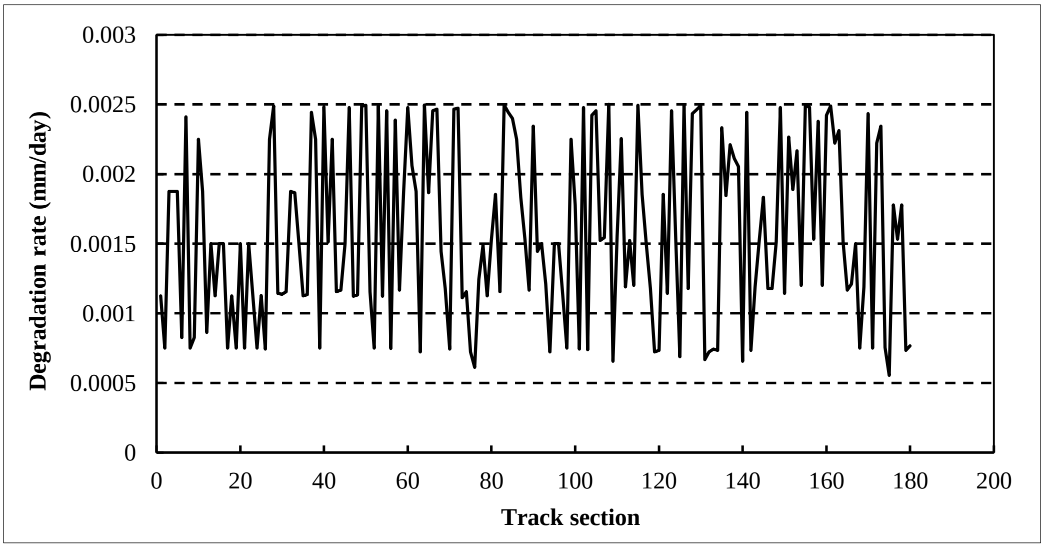

Figure 4. Degradation rate of the longitudinal deviation for the studied track

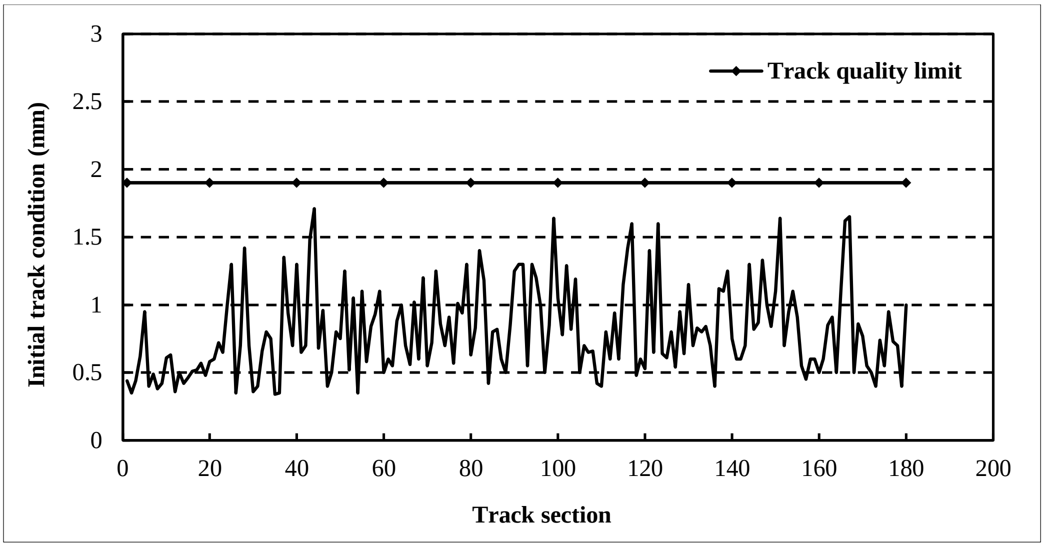

Figure 5. Initial track condition values for the studied track sections

4.2. Results

The advantage of this model can be summarized as the ability of considering variable values for the possession cost and the available workforce through the tamping planning process. This ability is helpful to the IM in order to put a suitable optimal schedule for this operation based on his private circumstances in the studied area. To illustrate this further, different cases are studied and the obtained results are compared and analyzed. These cases are as follows:

- First case (general case): it considers constant values for A^j and pc^j for all periods in the planning horizon,
- Second case (there is a wish to plan actions in a specific period(s)): the IM wishes to plan the maximum allowable number of tamping activities in a specific period (s) where the tamping machines and maintenance crews are available in that period(s) in order to fulfill the maximum interest from the available workforce. This situation can be achieved by assigning a small value for the possession cost of that period(s) to encourage the model to plan those actions through that period (s),
- Third case (there is no wish to plan actions in a specific period(s)): on the contrary of the second case, in this situation where the IM does not need to schedule any action in a specific period(s) because the workforce is not available in that period(s). This matter can be done by allocating a big value for the possession cost or a small value for the available workforce for that period(s) to push the model to avoid planning maintenance actions during that period(s), and
- Fourth case (mixed case): it involves planning in desired periods and non-planning in undesired periods at the same time. This condition can be performed by assigning small or big values for the possession cost and the available workforce for the related periods based on the considered circumstances.

For each case, the available workforce (A^j), the track possession cost (pc^j), the total number of tamping activities (Σx), the total number of possession periods (Σz), the DTC and the distribution of tamping actions on periods are presented in Table 1.

Table 1. Results of studied cases for tamping actions

Case	j	Available workforce and possession cost values in period j								Σx	Σz	DTC	Distribution of actions
		1	2	3	4	5	6	7	8				
1	A^j	65	65	65	65	65	65	65	65	219	4	249.75	Figure 7
	pc^j	10	10	10	10	10	10	10	10				
2	A^j	65	65	65	65	65	65	65	65	220	5	249.70	Figure 8
	pc^j	10	10	1	10	10	10	10	10				
3-i	A^j	65	0	65	65	65	65	65	65	233	4	261.12	Figure 9
	pc^j	10	100	10	10	10	10	10	10				
3-ii	A^j	65	65	65	0	0	65	65	65	254	4	284.40	Figure 10
	pc^j	10	10	10	100	100	10	10	10				
3-iii	A^j	65	65	65	65	65	65	65	65	233	4	346.41	Figure 11
	pc^j	10	100	10	100	100	10	10	10				
4	A^j	65	65	65	0	65	0	65	65	225	5	255.92	Figure 12
	pc^j	10	10	10	100	10	100	1	10				

Figure 6 presents the optimal schedule for tamping actions under given data which above mentioned and it represents the general case. In this figure, the planning horizon and the track sections are shown in the vertical and horizontal axes, respectively. Besides, the tamping tasks with total number of 219 are planned in four periods (i.e. 1, 2, 4 and 5, respectively) with DTC of 249.75. The distribution of these actions by period is illustrated in Figure 7. As observed in this figure, 24 actions are planned in the first period and 65 actions in each period of 2, 4 and 5, respectively. In this paper, it is assumed that this distribution represents the standard one for the studied problem (i.e. it represents the normal situation for the considered track and existing resources).

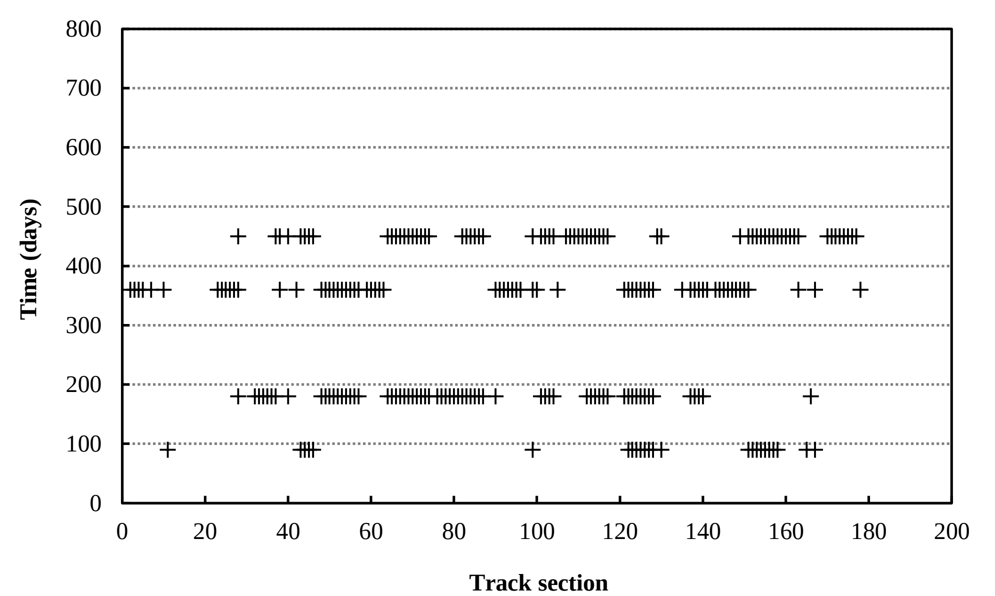

Figure 6. The optimal schedule for tamping operations for given data

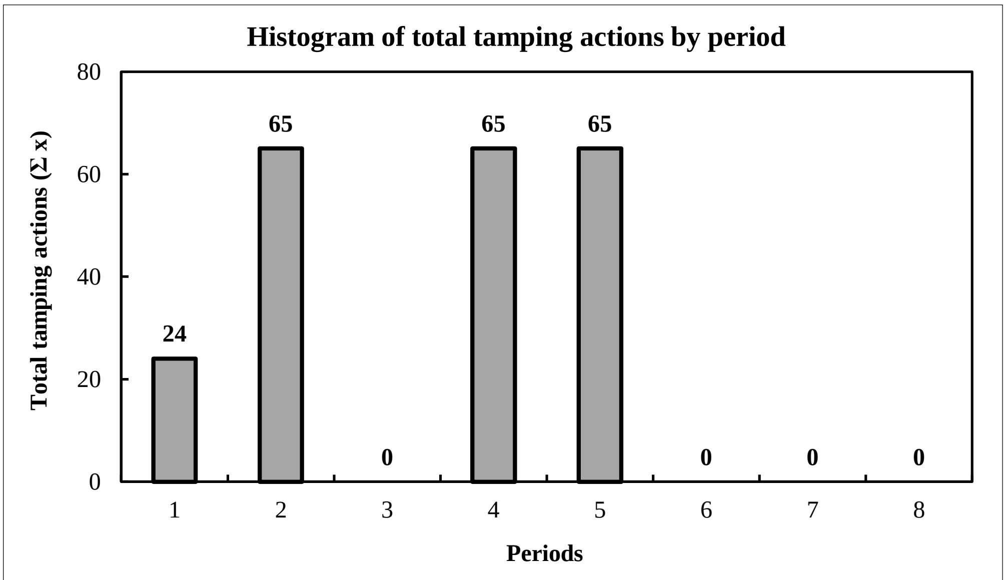

Figure 7. The standard distribution of tamping actions for the studied track for case 1

Practically and in some circumstances as it is mentioned above, it is preferred to plan a set of maintenance actions by the IM in a specific period(s) because during that period(s) –for example– the traffic on the studied track is not crowded or the machinery and manpower are available (second case), or maybe he tries to avoid planning any action in a specific period(s) because there are no enough equipment and crews to perform those actions during that period(s) (third case), or maybe he needs to mix the previous two situations together (fourth case) based on the available conditions in the considered area of the railway network.

In order to present an example for the second case which is mentioned in Table 1, it is assumed that the IM needs to plan the largest possible number of tamping actions in the third period but it is not allowed to exceed a certain threshold value (where it is assumed that it equals to 65 in this paper). It is found that the best way to achieve this demand is by taking pc^3 =1 with respect to the other values which are considered in the general case (Table 1).

Compared to the solution of the general case, the total number of tamping operations increases by one action and also the total number of possession periods increases by one period while the DTC reduces from 249.75 to 249.70 due to the decrease in the value of pc^3 from 10 to 1. The distribution of tamping works by period for this case is presented in Figure 8. It is noted in this figure that 14, 21, 65, 60 and 60 activities are scheduled in the time periods 1, 2, 3, 5 and 6, respectively. Moreover, the new constraints which are considered by the IM in this case led to a different distribution of tamping operations.

The third case which is provided in Table 1 consists of three instances as follows:

- Instance for one period (the IM wishes to avoid planning tamping jobs in the second period): this request can be achieved by taking (pc^2 =100) or (A^2 =0) or (pc^2 =100 and A^2 =0) with respect to the other values in the general case. The model in this example plans 61, 65, 65 and 42 maintenance actions in the periods 1, 4, 5 and 7, respectively as shown in Figure 9. The DTC value in this case equals to 261.12 which is more than the corresponding one in the general case by 4.55%. In other words, the new constraints led to an increase of the DTC value.
- Instance for two periods (the IM does not wish to plan maintenance actions in the fourth and fifth periods): this requirement can be performed by assuming (pc^4 = pc^5 =100) or (A^4 = A^5 =0) or (pc^4 = pc^5 =100 and A^4 = A^5 =0) with respect to the other values in the general case. Its distribution is presented in Figure 10. In this figure, it can be observed that the model schedules 59, 65, 65 and 65 operations in the time periods 1, 2, 3 and 6, respectively. The DTC in this example equals to 284.4 which is more than the value of DTC in the general case by 13.87%.
- Instance for three periods (the IM aims to avoid planning any maintenance operation in the second, fourth and fifth periods as much as possible): this demand can be only achieved by considering (pc^2 =pc^4 = pc^5 =100) with respect to the other values. In the distribution of this example which is illustrated in Figure 11, it is easy to see that the solver is enforced to plan tamping tasks in the fifth period (65 activities) although its possession cost is very high in order to get a feasible solution for the problem. In addition, the increase of the DTC value of this instance is 38.7% comparing with the general case. Here it should be denoted that by taking (A^2 =A^4 = A^5 =0) through the model, the solver does not find a feasible solution for the problem.

Therefore, it can be noted that the tight restrictions which are assumed during the previous three instances in the third case cause an increase of the total number of tamping actions and the DTC values compared to those in the general case, while no changes in the values of the total number of possession periods (Table 1).

Finally, the fourth case is shown in Table 1 by an example which assumes that the IM wants to plan the largest possible number of maintenance actions in the seventh period and avoid planning any action in the fourth and sixth periods simultaneously. This demand can be performed by taking (pc^4 = pc^6 =100 and pc^7 =1) or (A^4 = A^6 =0 and pc^7 =1) or (pc^4 = pc^6 =100, A^4 = A^6 =0 and pc^7 =1). The distribution of tamping actions in this case is shown in Figure 12. In this figure, the solver plans 25 actions in the seventh period and it does not schedule any action in the other two periods (i.e. 4 and 6 periods). Here also there is an increase of Σx, Σz and DTC values compared to those in the general case as presented in Table 1 and the DTC value is more than the corresponding one in the general case by 2.47%.

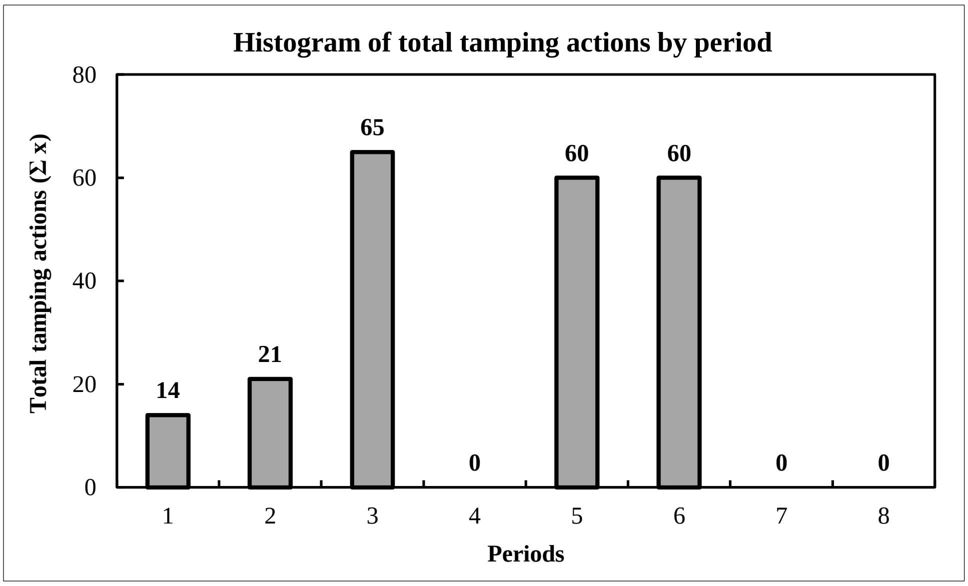

Figure 8. Distribution of tamping actions by period for case 2

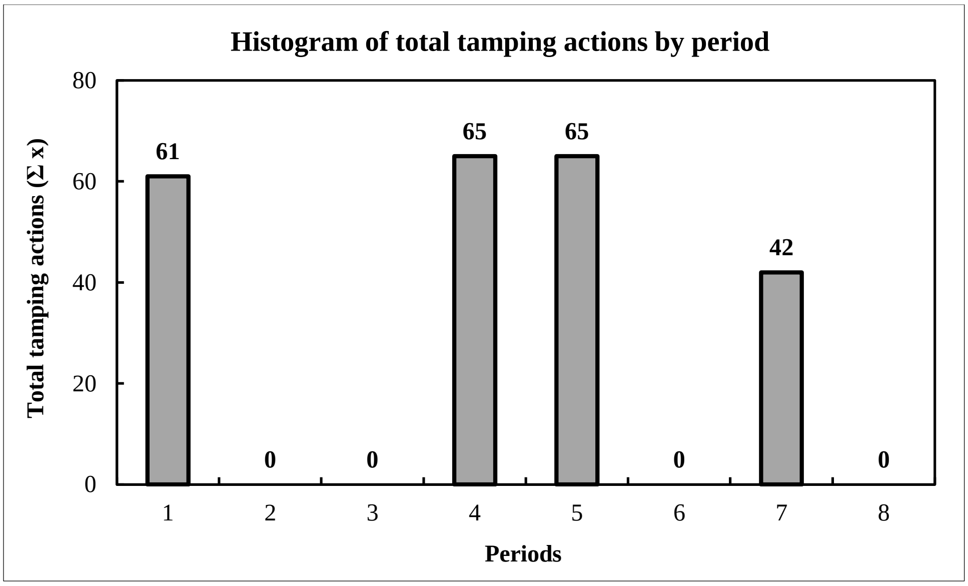

Figure 9. Distribution of tamping actions by period for case 3-i

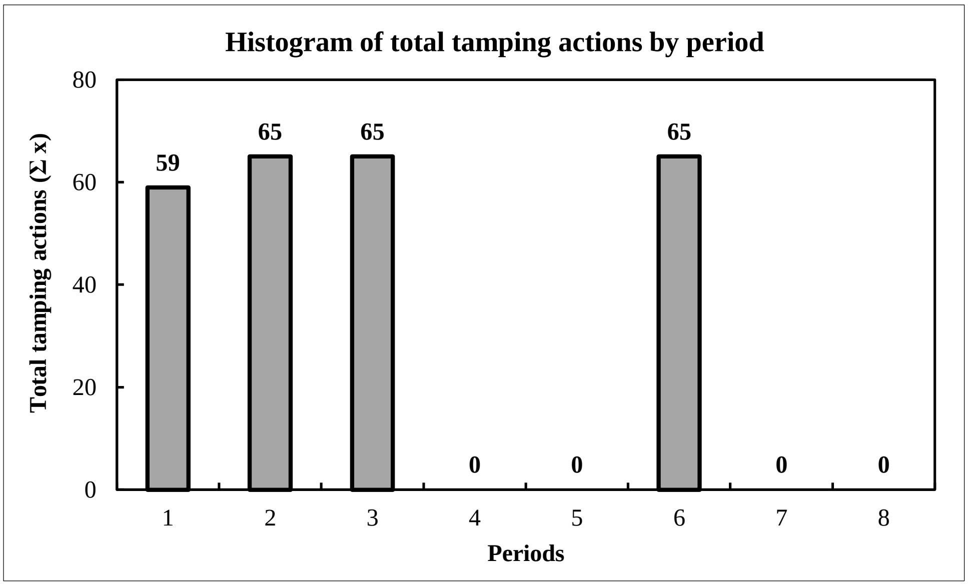

Figure 10. Distribution of tamping actions by period for case 3-ii

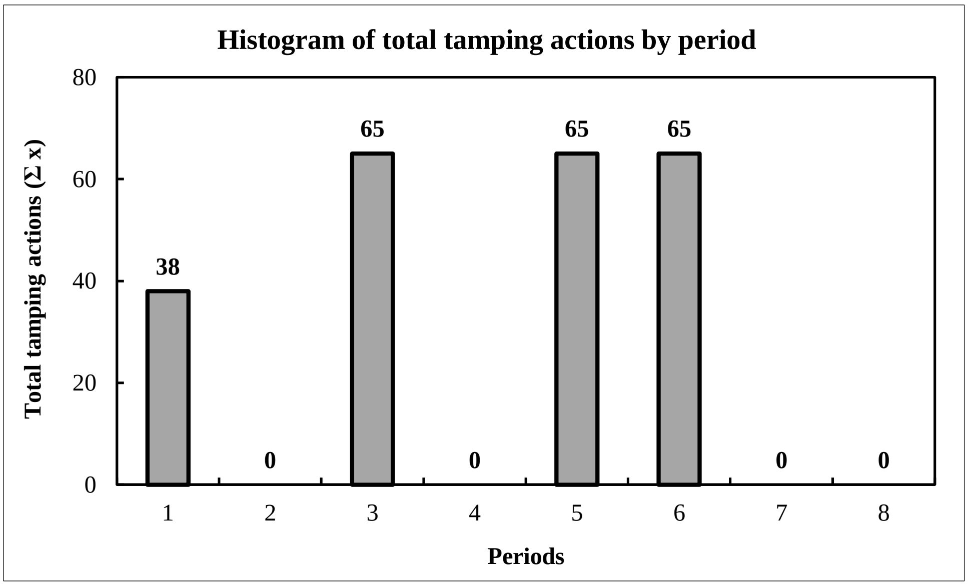

Figure 11. Distribution of tamping actions by period for case 3-iii

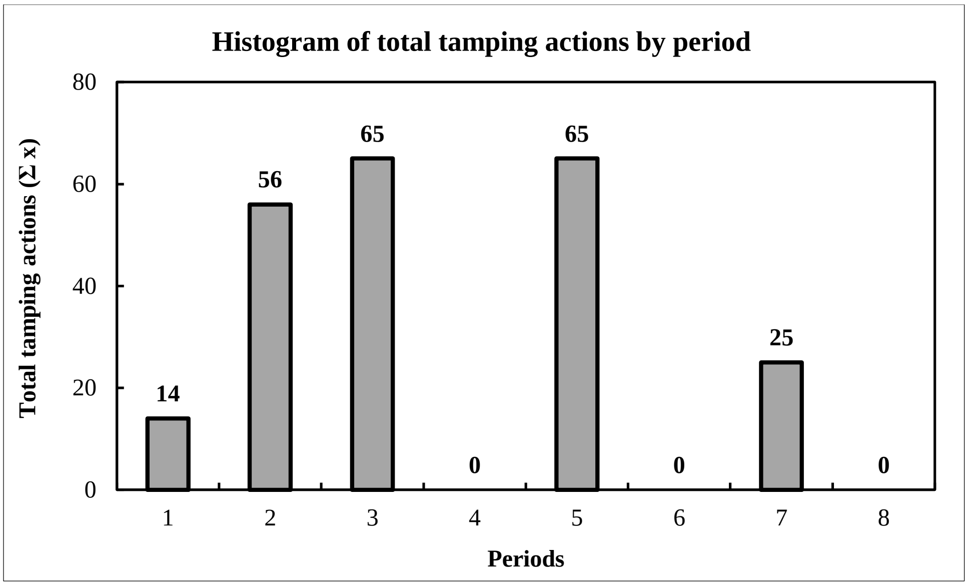

Figure 12. Distribution of tamping actions by period for case 4

Thus, the results show in the previous comparisons that consideration of tight restrictions in the studied problem leads to an increase of the total number of tamping actions and therefore an increase of the DTC. On the other hand, the IM can use the presented model as a good decision tool in order to obtain the optimal solution for tamping problem over the considered track under different conditions based on the track traffic and the available workforce during the planning horizon.

5. Conclusion and Future Research

In this paper, GM is improved by introducing available workforce restrictions in the model and considering constant/variable values for the track possession cost and the available workforce. This model seeks to obtain the optimum tamping plan for the studied track under different circumstances in a finite horizon. These circumstances depend upon the track possession cost and availability of machines and maintenance teams to perform the tamping activities on the considered track which may vary from one period to another in the planning horizon.

The analysis of the results shows that the developed model can be used as a suitable decision-making tool for the IM to get the optimal schedule for tamping operations under private situations based on the track traffic and the available resources through the time periods of the planning horizon. However, these situations may be led to an increase of the final cost.

The suggested model in this paper requires improvements in the coming work. Currently, the model only considers few constraints; there is a need to be extended to use other additional constraints such as budget constraints and environmental, operational and social constraints.

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7. Conflicts of Interest

The authors declare no conflict of interest.

8. References

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