DETERMINATION OF THE EFFECTIVE RAILWAY TRACK LENGTH TO BE MAINTAINED BY ONE TAMPING MACHINE

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ABSTRACT

Railways are facing an increasing demand challenge and the construction of new lines is evident in a worldwide scale. Furthermore, in the railway sector the development of effective technological solutions depends on achieving optimum infrastructure design, and less expensive solutions in a life cycle perspective. This perspective includes finding a cost efficient way on how to perform maintenance over the whole life cycle, especially in respect to the usage of heavy maintenance resources. Defining in the early design phase the optimum number of machines to use, based on a projection of the interventions that the track will require, is a research field that will, for sure, contribute to the above mentioned needs.

Planning maintenance on tracks has being a developing area, leading to avoidance of disruptions on train traffic, damages on vehicles and higher costs by inefficient usage of the track components. Based on this, the research for a most cost effective maintenance plan has been directed towards finding a degradation theory for sections of the track and then assigning the interventions according to this plan. The implementation of these findings in a linear extensive infrastructure, such as railways, could be used to define a more effective maintenance plan, assess the efficiency of using the intervention means and thus deliver an adequately estimate the necessary means to produce track maintenance.

This paper aims at the development of a methodology that defines the optimum length of track that would undergo maintenance works by one track maintenance tamping machine. The methodology proposed follows a recommended track quality standard, taking into account the execution capacity of a tamping machine in a scenario where the intervention schedule is optimized in a long term perspective. It uses a meta-heuristic process (simulated annealing) to deliver an optimized intervention schedule and the model is applied to several track length configurations.
Keywords: railways, track maintenance, maintenance planning, predictive maintenance, tamping machines, machinery capacity, simulated annealing

INTRODUCTION

The new demands imposed on railways, such as increasing capacity, higher speeds, safety improvement and cost-effective management of the system, are having an impact on the way track maintenance is performed. The railway track is a linear infrastructure with long length and its parts deteriorate in different ways over time, due to the passage of trains and the behaviour of the infrastructure itself. In terms of efficient maintenance, this fact requires prior knowledge of when and where the track will require interventions. Lately, this question has been addressed with considerable results, leading to degradation models whose outcome indicates a “quality level” of a certain segment of track in a certain period of time. The dependence on these models is expected to increase as they became more reliable with improvements on track measuring and data analysis.

The impact of this new achievement is not restricted to the avoidance of failure occurrences by intervening before a certain section reaches a predicted minimum level of quality, in certain time. In fact, it paves the way for a new approach towards how to perform track maintenance, especially by allowing for long-term maintenance planning. For an operational railway line with known behaviour or one under study, with an expected behaviour, this maintenance planning refers to the definition, in advance and for a period of upcoming years, of the optimum way to maintain the railway line through the accomplishment of a defined quality level with minimum maintenance costs and maximum performance of the existent track.

The present work develops further the above-mentioned idea and studies the issue of the required logistical means for track maintenance interventions, through the identification of the most effective railway track length that could be handled by one single intervention machine. In this study, the tamping machine was considered. The problem was addressed through the optimization of maintenance scheduling in a long term perspective for many track lengths configurations. The optimization of the maintenance scheduling guarantees an effective use of the machine’s operational capacity, promoting a more cost effective way to produce maintenance, in respect of recommended track quality levels. A meta-heuristic technique – simulated annealing – was applied to deal with the complex combinatorial problem. The model calculates unitary maintenance costs, and its application produces results about the effective track length to be handled by one intervention machine.

This paper begins with a description of previous approaches in maintenance planning and the use of simulated annealing, then it describes the objectives of the proposed model and its underlying methodology. Then the model is applied for different track lengths configurations of a single railway line and the corresponding results are presented. Finally, conclusions are drawn and implications for future research and further extensions of the model are discussed.

LITERATURE OVERVIEW

According to Oke (2006), maintenance scheduling research represents a large portion of contemporary operations management literature and based on the qualitative and quantitative approach distinction, the stream of quantitative studies can be subdivided into methods / techniques and applications in various contexts (see Figure 1). Thus, in this framework, the purpose of this paper is to present the application of the simulated annealing technique in the case of long-term railway track maintenance scheduling, particularly used to address the determination of the effective track to be handled by one tamping machine.

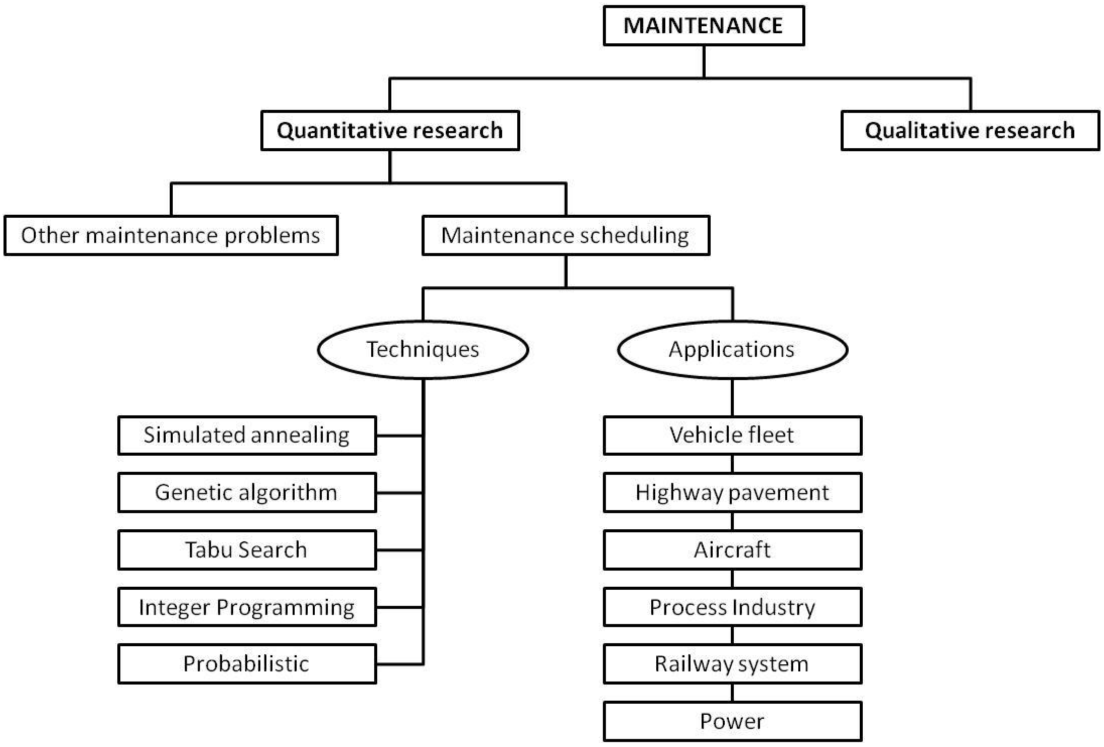


Figure 1 - Methods and applications of maintenance scheduling (based on Oke, 2006; modified by the author)

Dekker (1995) defines a maintenance optimization model as a mathematical model in which both costs and benefits of maintenance are quantified and in which an optimum balance between both is obtained. He also identified the following four aspects of maintenance optimization models (Dekker, 1995):

1. a description of a technical system, its function and its importance,
2. a modelling of the deterioration of the system in time and possible consequences for the system,
3. a description of the available information about the system and the actions open to management and
4. an objective function and an optimization technique which helps in finding the best balance.

Track maintenance scheduling involves the allocation of maintenance activities to time windows and crews to activities and is formulated as an integer programming model (Higgins et al, 1998).

Higgins (1998) developed a railway track maintenance model that combines multi-project and crew scheduling, using the tabu search heuristic technique. More precisely, the objectives of the model were a combination of minimizing the prioritized finishing time of each activity as well as expected interference to (and from) scheduled t rains. The implementation of the model in a railway corridor in Queensland showed that the best possible solution achieved a 6.3% improved objective function value over a schedule constructed manually using expert knowledge on maintenance activities´ scheduling and crews´ allocation.

Zhao et al (2009) developed a methodology for the optimization of the renewals of track components within a finite planning horizon, through a genetic-algorithm-based model. To achieve this, the model maximizes the cost benefit by combining the renewals of components for a section of track during a specified planning horizon. They also state that other techniques based on meta-heuristics may also be equally valid as a genetic algorithm.

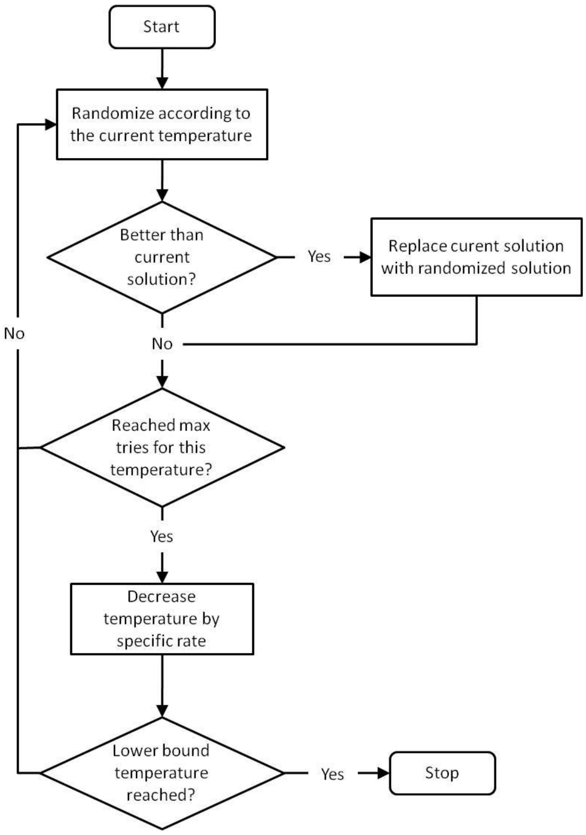
Lake and Ferreira (2002) developed a model to solve a binary integer non-linear programming problem of reducing the conflict between the trains and track maintenance by the short-term scheduling of the maintenance and the required resources. They applied the heuristics techniques of Simulated Annealing, Local Search, Multiple Local Search and Tabu Search and concluded that the most appropriate solution method to solve the short-term maintenance scheduling problem, as formulated in their paper, is Simulated Annealing.
Simulated annealing (SA) is a compact and robust technique, which provides excellent solutions to single and multiple objective optimization problems with a substantial reduction in computation time, aiming at obtaining an optimal solution of a single objective optimization problem and a Pareto set of solutions for a multi-objective optimization problem (Suman and Kumar, 2006). It belongs to the category of local search meta-heuristics (simulated annealing, tabu search). It is also referred to as Monte Carlo annealing, probabilistic hill climbing, statistical cooling, and stochastic relaxation (Aarts and Korst,1989; Lee and Zaider, 2004).

The development of simulated annealing technique, in its original form, is attributed to Metropolis et al (1953) and it was used for solving combinatorial optimization problems. In a later time, in the mid 1970's, Scott Kirkpatric and colleagues developed further this technique, aiming originally at the better optimization of the design of integrated circuit (IC) chips (Heaton, 2005). Simulated annealing was inspired by the physical annealing process in metallurgy (Kirkpatrick et al, 1983; Cerny, 1985; König and Beißert, 2009). More precisely, annealing is a process in which a solid is heated beyond its melting point and then cooled slowly and carefully into a perfect lattice, with the crystalline structure of the perfect lattice representing a minimization of free energy for the solid, while the cooling process determines if the ground state is achieved or if the solid retains a locally optimal lattice structure with crystal imperfections (Lee and Zaider, 2004). An overview of this process is depicted in

Figure 2, but it has to be noted that the inputs and parameters are modified accordingly, depending on the context1 of implementation. In general the following requirements should be met (Kirkpatrick et al, 1983; Lee and Zaider, 2004):

1. a concise representation of the state space,
2. a method for randomly generating state transitions,
3. an objective function measuring the cost/benefit of transitions, and
4. cooling schedule parameters and a stop criterion.

The principal shortcoming of simulated annealing is that it often requires extensive computer time and implementation modifications generally strive to retain simulated annealing's asymptotic convergence character, but at reduced computer run-time (Henderson et al, 2003). Furthermore, simulated annealing can be combined with other methodologies and techniques, as derived from the literature, as for example the integration of genetic algorithms with local search techniques (simulated annealing, tabu search, steepest hill climbing etc), known as memetic algorithms (Budai-Balke, 2009), or combinations of local search techniques, as for example a Tabu search / Simulated annealing hybrid algorithm (Burke et al, 1997). For a more detailed overview of the methodology, the reader is prompted to see, among others, Bertsimas and Tsitsiklis (1993), Collins et al (1988), Tovey (1988), Eglese (1990), Tan (2008) and Talbi (2009).



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[1] Simulated annealing has been used in many different contexts, such as for example school timetables (Abramson, 1991), airline crew-pairing (Emden-Weinert and Proksch, 1999), health treatment planning (Lee and Zaider, 2004), construction scheduling optimization (König and Beißert, 2009) etc.

Figure 2 - Overview of the simulated annealing process (Heaton, 2005)

OBJECTIVES

The present work aims at finding the track length for which a tamping machine can operate following a recommended quality standard, having in account the execution capacity of a tamping machine in a scenario where the intervention schedule is optimized in a long term perspective and it ensures the lowest intervention cost per section.

When designing a new railway line or in the situation of current operation, it is necessary to plan the maintenance of the railway track. Planning track maintenance is important in operational terms – i.e. to define an effective schedule for crews and machines – and it is also important to forecast the costs regarding the future years and then pursuit an optimum cost solution. Railway maintenance involves a great number of tasks; however in this paper attention is given to the mechanized tamping performed by tampers. The tamping machine´s objective is to restore the initial position of the track, which suffers from displacements because of the passage of trains. The acquisition cost of this type of machinery is so high that the existence of a methodology for the definition of the required number of tamping machines for a certain length of track is more than required.

METHODOLOGY

The methodology proposed in this paper is based on the determination of the track length along which one tamping machine would intervene. Thus, the proposition that this paper develops on is that the optimal length of track to be treated by one machine is obtained by an optimal schedule of interventions respecting a quality standard for the track along its life cycle.

In this perspective, obtaining an optimal schedule for the interventions means delivering an intervention plan that takes full advantage of the execution capacity of the machines without performing more interventions than the ones required by the infrastructure. By capacity of the machines, one means the number of sections that a machine is able to perform in a certain time period. A major factor to determine the capacity is the available track possession time period that is usually allocated - to perform maintenance works. In the current model the capacity of the machines was considered constant, and a mean value of sections that could be performed in a period of time was adopted. This simplification was found not to influence the methodology for the calculation of the effective length of track that could be handled by one machine.

The extensive length of any railway line introduces the problem of allocating means of intervention from the maintenance yards to each location of the line that requires maintenance works. The logistic costs regarding the machinery represent a relatively high percentage of the total maintenance costs and the advantage of clustering sections to be performed in the same period of time is obvious. The model presented here uses the Simulated Annealing (SA) technique in order to achieve a high degree of clustering optimality and considers the operating costs of performing an intervention and the travel costs of the machine from its maintenance yard to the sections and back.

By using the SA technique, an initial schedule is established that is feasible to be performed by the machine, according to its defined capacity. Thus, the meta-heuristic produces marginal changes that correspond to the postponement of a certain intervention to the next time period and the performance of another intervention in an earlier period; always assuring though the feasibility of the solution. The cost of each trial is obtained, and then compared with the best solution found. A rule of acceptance determines if the algorithm adopts or not a higher cost trial to be modified next (in the same way), while the algorithm continues this sequence for a defined number of iterations.

A relevant aspect of the meta-heuristic used is that it randomly chooses every period of time to change, every section to postpone or to perform earlier and also, in every trial, the way to accept a higher cost solution is derived randomly.

The methodology used consists of the following assumptions:

- A railway line, with a certain length, is divided into sections;
- a maintenance yard is placed in the middle of the railway line, where a tamping machine is settled;
- the costs involved are the travel costs (of moving the machine from the yard to the sections to operate and between sections), the operational costs of the machine (when performing the sections) and the acquisition cost of the machine (considering - the amortization cost for the chosen analysis period);
- the machine has a limit of sections to perform in each period of time;
- the period of analysis considered is representative of an average time period regarding the demand of interventions of an infrastructure (does not correspond to all life cycle);
- different deterioration behaviour is assigned to each section, based on the evolution of the standard deviation of the longitudinal level (a particular track measure that is used to determine tamping);
- the track follows a linear deterioration rate that is kept constant after each performance. The assignment of different deterioration rates to sections is made randomly based on a normal distribution with defined average and standard deviation;
- the average and the standard deviation for the generation of the deterioration rates is representative of an average time period regarding the demand of interventions of an infrastructure;
- following the UIC (International Union of Railways) recommendations, 3 levels of track quality are considered, defined by boundary values for the longitudinal levelling of the track. The interventions could only take place between defined boundaries;

- the evaluation of the track quality in each time period is done by the percentages of track in each level of quality (see column 3 of Table I). The overall quality for the plan of interventions is obtained by the average of those percentages for each level of quality.

Taking into account the above mentioned assumptions, the SA algorithm was structured on five main steps:

1. Elaboration of the initial basic solution;
2. Establishment of a new solution by finding a feasible “neighbouring” solution;
3. Calculation of the cost for the new solution;
4. Analysis of the acceptance for the new solution;
5. Procedure of conducting the iterations and changing of epochs (cooling rate).

For the elaboration of the initial basic solution, the model receives as an input a deterioration matrix (sections versus time periods) which is created in advance, according to the 5th, 6th and 7th assumptions. Thus, the algorithm reads the number of sections to be performed in all time periods. If in any case the number of sections exceeds the capacity limit of the machine, it schedules that intervention for an earlier period. That intervention occupies the previous time period cell in the matrix. By scheduling an intervention for an earlier period, all its “life cycle” (i.e. its deterioration evolution) from that time period until the end of the period of analysis is affected since the whole time series evolution is offseted one time period before. The deterioration matrix was designed in a way that it includes extra deterioration values beyond the end of the analysis period enabling the entrance of new data when the matrix is offseted in a certain time period.

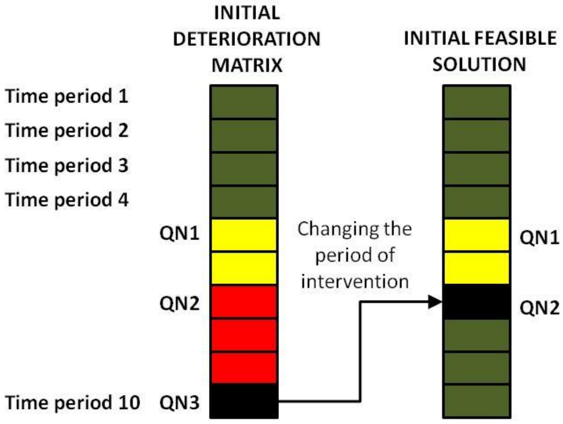


Figure 3 – The offset of the initial deterioration matrix to the Initial Feasible Solution (IFS)

Another main criterion for the establishment of the initial basic solution (IBS) is that all interventions are rescheduled for a certain superior level of quality (an earlier time period). When the algorithm reads the initial deterioration matrix, for each section a certain number of tamping cycles is shown. Those tamping cycles finish in the limit state of intervention (QN3 level from Table I). Departing from that position of intervention, the IBS is found by rescheduling to an earlier time period until at least a certain level of quality, higher than the initial one, is established. This is done in combination with the aforementioned criterion of the capacity limit of the machine, as described in the previous paragraph.

Table I – Quality levels according to the UIC 518 standards (UIC 518 – Annex D (02/1998)

Quality levels	**Description**	**Recommendations**	**Average Defects in Longitudinal Leveling for 200km/h < v ≤ 300km/h**
QN1	Refers to the value which necessitates observing the condition of the track or taking maintenance measures as part of regularly planned maintenance operations	50% of the track with quality superior or equal to QN1	1,0
QN2	Refers to the value which requires short-term maintenance actions	40% of the track with quality located between QN1 and QN2	1,3
QN3	Refers to the value which corresponds to an unwanted situation	10% of the track with quality located between QN2 and QN3	1,69

The moving selection rule (MSR) so as to find a feasible “neighbouring” solution is much related with the last criterion for the IBS. Previously, it has been stated that to establish the IBS the track quality is raised until a certain level. That level is near to the highest quality boundary allowed to perform an intervention. Thus, the MSR is trying to find a period of time with interventions that are possible to postpone. Once a section of that type has been found, the algorithm verifies if in the next time period there is enough capacity for the machine to perform one more section (the postponed one). If this capacity exists the referred intervention is allocated one period later, but if the capacity is not enough, then one of the interventions of that period will be chosen so as to be performed earlier.

The MSR has to take into account the impact of any “movement” in the context of the full period of analysis. Thus, when the postponement of an intervention is in analysis it has also to be defined which of the cycles will contribute to that “movement”. This rule has an impact on the number of the possible “neighbourhoods” to test, respecting the idea of finding any feasible “neighbouring” solution. This way, there are more possibilities for the second section to adapt for each intervention cycle chosen in the first section.

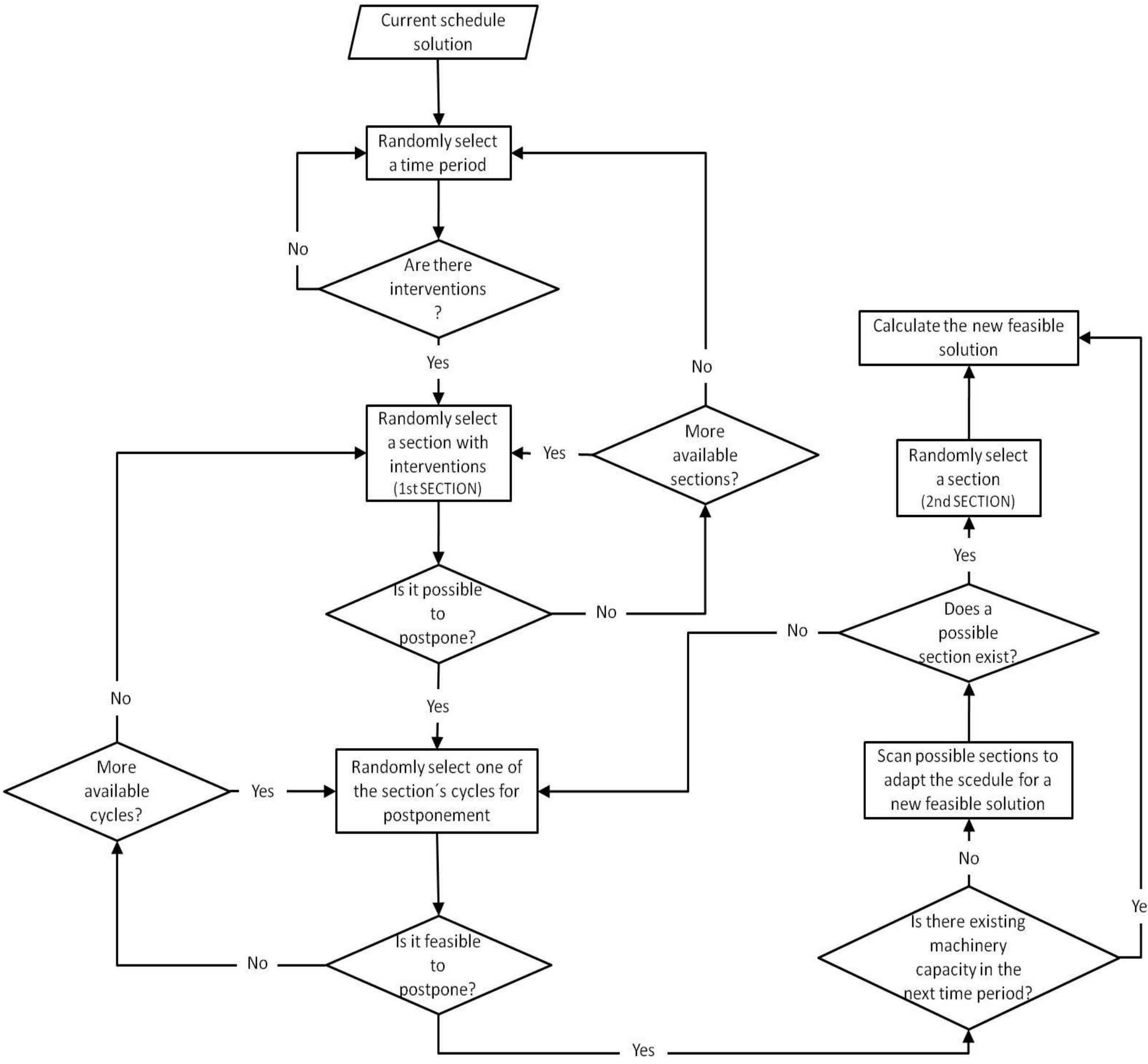
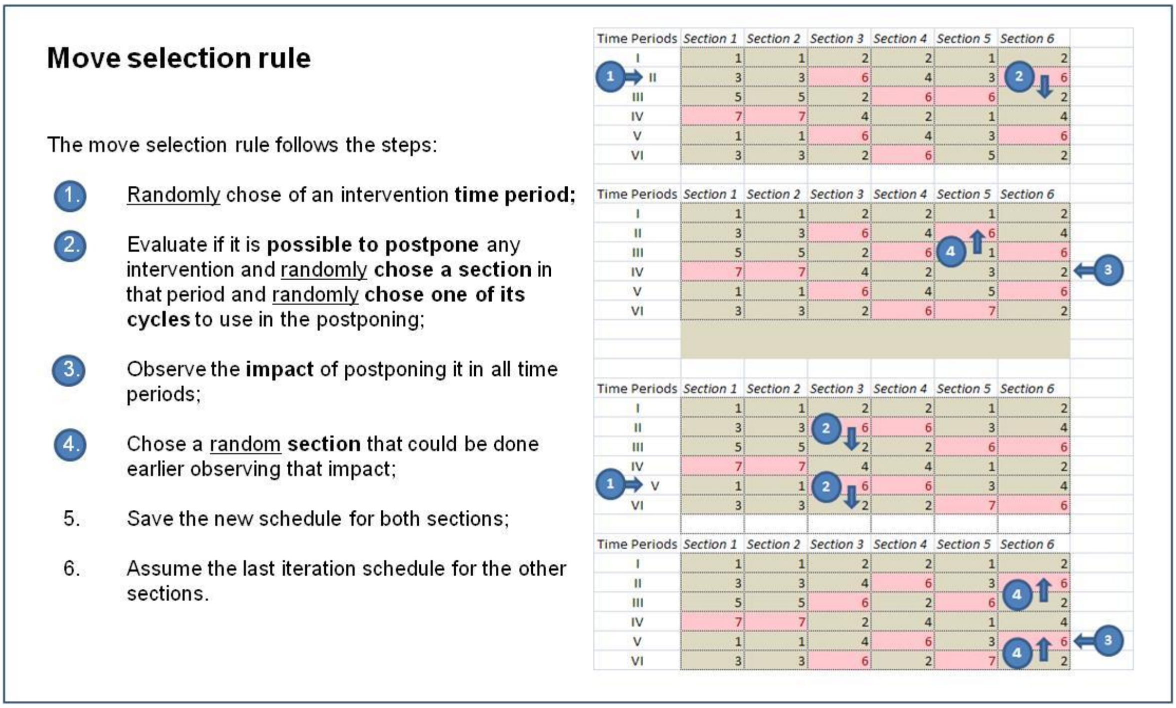


Figure 4 - Logical flowchart of the MSR algorithm

To resume, the MSR algorithm comprises of four randomized functions (see Figure 4):

1. randomly picks a time period where there are sections whose interventions are possible to be postponed;
2. randomly chooses one of those sections (called the first section);
3. randomly chooses one of the intervention cycles located earlier than the chosen time period it;
4. from all the possible sections that are affected by the movements of the first section, it randomly picks one section (called the second section).



Move selection rule

The move selection rule follows the steps:

1. Randomly chose of an intervention **time period;**
2. Evaluate if it is **possible to postpone** any intervention and randomly **chose a section** in that period and randomly **chose one of its cycles** to use in the postponing;
3. Observe the **impact** of postponing it in all time periods;
4. Chose a random **section** that could be done earlier observing that impact;
5. Save the new schedule for both sections;
6. Assume the last iteration schedule for the other sections.

Time Periods	Section 1	Section 2	Section 3	Section 4	Section 5	Section 6
I	1	1	2	2	1	2
II	3	3	6	4	3	6
III	5	5	2	6	6	2
IV	7	7	4	2	1	4
V	1	1	6	4	3	6
VI	3	3	2	6	5	2

Time Periods	Section 1	Section 2	Section 3	Section 4	Section 5	Section 6
I	1	1	2	2	1	2
II	3	3	6	4	6	4
III	5	5	2	6	1	6
IV	7	7	4	2	3	2
V	1	1	6	4	5	6
VI	3	3	2	6	7	2

Time Periods	Section 1	Section 2	Section 3	Section 4	Section 5	Section 6
I	1	1	2	2	1	2
II	3	3	6	6	3	4
III	5	5	2	2	6	6
IV	7	7	4	4	1	2
V	1	1	6	6	3	4
VI	3	3	2	2	7	6

Time Periods	Section 1	Section 2	Section 3	Section 4	Section 5	Section 6
I	1	1	2	2	1	2
II	3	3	4	6	3	6
III	5	5	6	2	6	2
IV	7	7	2	4	1	4
V	1	1	4	6	3	6
VI	3	3	6	2	7	2

Figure 5 – Two examples of random selection of the cycle to move on the first section and the subsequent adaption of the second section. Red cells refers to interventions

As mentioned earlier, all the movements are constrained between a maximum and a minimum level of deterioration, thus it is within these boundaries that the possible movements are analysed. If in any of the randomized functions from 2 to 4 - a movement is rejected, the algorithm records the non possible execution and proceeds again in a random selection in the respective function. Finally, if in a certain function it is not possible to find a feasible solution, the algorithm repeats the previous function.

The cost calculation of a feasible solution, known in SA terminology as the temperature, is represented by the calculation of the maintenance costs (variable costs). It corresponds to the sum of the operating costs of performing an intervention and the travel costs due to the displacement of the machine in each time period. It is assumed that for each time period, the machine leaves the maintenance yard, travels to the first section of intervention, then travels to following sections and only returns to the yard after the final section scheduled for that time period is performed. This assumption considers that the machine travels in an unhindered way, from one location to another - along the track line. It has to be noted that this simplification has been assumed in this model, but in reality the operation of those machines is a much more complex task.

Preventive maintenance is usually performed in the night track possession period. Commonly it is a 5-hour period, during which the machine travels to the intervention-locations, with the possibility of stopping at sidings located along the line. By stopping in sidings there is no need for the machine to return to its maintenance yard. It only returns if it is logistically convenient or for its own maintenance. When the machine is stopped in the sidings, the crew is then transported to the respective yard. It is evident that the number of sections that could be performed by one machine depends on the efficiency of that particular machine (number of meters performed per hour), but the most determinant factor is the time possession period. This way, the precise calculation of the execution capacity of a machine is only obtained by the simulation of all the displacements from yards to sections, from sections to sidings and between sections. Thus, by optimizing the logistics of the machines, gains for the capacity of the machines can be obtained. On the other hand, there are relevant costs due to the displacement of the crews from the sidings to the maintenance yards and vice-versa. This level of analysis requires a very detailed planning and optimization process, which in the outset prescribes the high level of complexity of the model presented here.

In the framework of this model, capacity is defined by the number of sections that could be performed in the same time period and this number is kept constant through time. The travel costs will direct the algorithm towards adopting closer sections to intervene. As the detailed operational level is neglected, the time periods adopted should also be greater than daily or weekly period, so the adequate period considered in this model is a month. A distance matrix assists the calculation of the travel costs and a unitary travel cost is defined in advance. The other part of the variable costs calculation, the operational cost to intervene, forces the algorithm to schedule less number of interventions; a unitary cost of operation per section is considered. The objective function for the cost calculations is presented herewith, and in Figure 6 a graphical representation of 14-section track length configuration for the time period i is presented.

$$Z_i = \sum_{t=1}^{n} [(T_c + \ D_c * d_{Yard-s1}) + TI_{s2} * (T_c + \ D_c * d_{s1-s2}) \\ + \ TI_{s2} * D_c * d_{s2-Yard} + \ (1 - TI_{s2}) * (\ D_c * d_{s1-Yard})]$$

Z_i	Cost for iteration i
n	Number of time periods in analysis
D_c	Machine Travel Cost per km
T_c	Machine Operating Cost per section
TI_{s2}	Binary variable marking the execution of works in a second section
$d_{j\text{-}k}$	Kilometric distance between points j and k

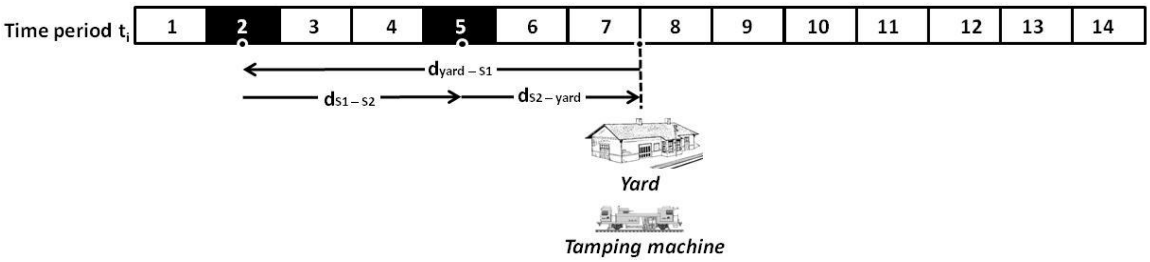


Figure 6 – Graphical representation of a 14-section track length configuration for the time period i

The final step in the SA algorithm is the procedure of conducting the iterations and changing of epochs (cooling rate). The SA algorithm runs a defined number of feasible iterations in each epoch. The number of epochs defined by this model was derived from the observation of when the optimum solutions would emerge throughout the trials. The epochs differ by the degree of acceptance regarding a higher cost solution found. If that solution is accepted the model will apply the MSR in this last solution. The degree of acceptance will decrease from epoch to epoch. That decrease, known as the cooling rate, must be adapted to the particularities of each optimization. For this problem, it is believed that the adequate cooling rate must be low, adopting a linear trend with values between 0,7 - 0,9. The justification lies in what was defined for the MSR: the adopted “movements” could represent such a marginal change in the context of an application with great number of sections and time periods that a better solution could be identified through a more “continuous” search – adopting a soft reduction of the “temperature”. Regarding the number of iterations, this value should allow the model to consider any possible combination of interventions. For n number of sections, and considering for each tamping cycle the possibility to perform the intervention in 10 periods of time, the total number of possibilities just for one tamping cycle is equal to 10^n. It represents such a huge number that the number of iterations seems to rely on the capacities of the computer processor, as it was verified in the application of the model.

For each iteration of the SA algorithm, an assessment of the quality of the track is made, obtained from the respective intervention schedule. The quality assessment is made for each time period and then an average value to evaluate the whole of the period of analysis is considered. This evaluation will be used to select one of the “local optimum” solutions, those that are closer to the aforementioned recommendations of UIC. This way, the best cost solution found could not be considered as a determinant of the optimum length of track that could be performed by one machine and instead opt for another “local optimum” that respects more those recommendations.

The methodology proposed here applies the SA algorithm described to different lengths of track. The trials of different lengths must take into account:

- the preparation of new distance matrices for each particular length, positioning always the maintenance yard in the middle of the line;
- the generation of new deterioration matrices that must correspond always to similar normal distributions of the deterioration rates generated randomly; and
- the adjustments in the SA algorithm concerning the input of the new length and the threshold for raising the quality from the limit intervention to a certain superior level of quality (mentioned earlier in the elaboration of the IBS).

The solution for the effective length of track to be performed by one tamping machine is obtained through the lowest unitary cost (cost per section, since all sections have equal length) of the different local optima, and for each trial of different lengths that are closer to the quality standards adopted. That unitary cost is equal to the sum of the costs obtained in SA (overall maintenance cost for the period of analysis) plus the acquisition cost of the machine (considering the incurred cost in the period of analysis) divided by the number of sections.

APPLICATION

According to the proposed methodology, the application of the model was implemented for several configurations of track length. The several configurations differ only in the number of sections, and 7 lengths of single railway lines were adopted, that is140 km, 160 km, 180 km, 200km, 220km, 240km and 260km. In all cases the maintenance yard is positioned in the middle of the line. The adopted length for the sections is 10 km and this length is the same for the several track configurations, i.e. the 7 configurations have respectively: 14, 16, 18, 20, 22, 24 and 26 sections.

The life cycle perspective of the model leaded us to the adoption of a 5 years period of analysis. This consideration does not correspond to the current expectancy of a railway infrastructure (30 - 40 years), however it was found reasonable that the adoption of this short time frame as representative of a life cycle behaviour, is sufficient enough to confirm the applicability of the model and is also more suitable for calculations. Thus, the period of analysis will be the same for the several configurations of track length. This period of analysis is divided in time periods and the time period adopted was a month, based on the justification presented in the methodology. This way, there will exist always an intervention plan compound of 60 time periods (12 months * 5 years).

The capacity of the machine, i.e. the number of sections that a machine could intervene in a time period, was based on the possession track period usually given in a daily basis for maintenance, on the section length and on the performance of the machine. Thus, usually, 5 hours per day are allocated to perform maintenance. If one considers that from those 5 hours only 2 in average are used for real operation – executing tamping – and considering also (as derived from the machinery producer's data) that a machine performs 500 m/h, in 2 hours of effective work per day, 1 km of track length undergoes maintenance interventions. The remaining 3 hours of the possession period are considered as logistical required time. Adopting a week of 5 days, one could reach an average value of performance of 5km per week, reaching roughly a monthly performance value of 20 km. This approximated value is exactly the length of two sections, as defined above.

The machine costs can be classified into 3 types: travel costs, operation costs and acquisition costs. The two first costs are derived as a compound value from personal communication with private contractors, which stated that in average the cost to execute a tamping work is 5000€/km (current prices 2010). As stated above with performances of 500m/h, during the 2 hours of effective work 1 km of track can be treated, i.e. the price of 1 night of work is 5000€. This cost is seen as an average cost independently of the location of the intervention, and without taking into account the depreciation of the machine. To derive the travel cost from this compound value, it was assumed that the 3 hours of non effective work refer to the logistic costs, which are a function of the distance from the yard to the intervention section. Considering an average access distance of 100 km, for one night of works, the outward and return journey of the machine (i.e. from its maintenance yard and back) delivers a trip of 200 km. Those 3 hours spent on logistical requirements is equal to the 3/5 of the 5000€ per night of work and, that means the part of the logistic cost per night is 3000€. Thus, dividing 3000€/200km we conclude to a logistic cost of 15€/km-travelled. Following the same reasoning, the operational cost to consider counts for the remaining 2/5 of the 5000€ for the 1 km maintained and it comes up to 2000€/km-operated. The final values adapted for a 10 km section, considered for the present model are:

Travel cost: 150€/km travelled (15€/km adapted for 10 km section)

Operational cost: 20000€/section (2000€ adapted for a 10 km section)

The acquisition cost of a machine is considered to be 10 million €, derived from personal communication with machinery professionals. If one considers that a machine has a life expectancy of 20 years, for the period of analysis of 5 years, the respective depreciation cost for that period would be roughly considered as 2,5 million € (1/4 of its life expectancy).
As mentioned in the methodology, the track deterioration is assessed by the degradation of the longitudinal levelling. It is assumed that the track sections will have different levels of deterioration rates (linear ones), assigned randomly to each section using a normal distribution. The distribution of those rates throughout all sections was done with a random number generating procedure. The generation was done for each configuration of track length, adopting similar normal distributions with average equal to 4 mm/100MGT (million gross tonnes) and standard deviation of 1mm/100MGT. It was also assumed that the linear trend will not change after the execution of the tamping interventions, so it will remain constant over time for each section; this is a simplification -, since usually this linear trend changes slope after each tamping, but this parameter will be incorporated in the extension of the current model in the future.

The complete expression for the level of deterioration of the sections is shown herewith:

$$SD_{ll} = C_0 + C_1 * T$$

Where SD_{ll} represents the standard deviation for longitudinal levelling defects, C_1 is the linear rate derived randomly, T is the million gross tonnes commonly used in basis “100” and C_0 is the initial standard deviation of levelling defects for each cycle of tamping. The parameter C_0 is considered in the model as a constant value (0,5 mm) however in reality C_0 evolves each time a tamping action is performed. The need to keep it constant is related to the definition of unique tamping periods assigned to each section, which enables for a faster running of the algorithm when performing the intervention movements along the time periods. The evolution of MGT in each time period was assumed constant, with a value of 1,5 MGT/time period, reaching a final value of an accumulated 90 MGT in the end of the period of analysis. The adoption of this value comes from the consideration of 50000 gross tones/day/direction, which is a - value derived from Lichtberger (2005).

RESULTS

The implementation of the model in the numerical framework described earlier in this paper and the consequent analysis of the results, present interesting differences between the several configurations of track length that were tested. The very first difference is the total number of iterations required by the several configurations so as to conclude the algorithm of the model. More precisely, the number of iterations lies between around 7000 iterations for the 140 km configuration and almost 10000 iterations required for the 260 km configuration. An even more expressive difference lies in the number of movements tested until reaching the end of the model: it shows a number of movements of around 800 to the 140 km length solution in opposition to around 5000 movements for the 260 km length solution. Another difference that was noticed is relevant to the computational time between the trials mentioned earlier. The most obvious reason for this, is the different dimension of the configurations tested, by adding one more section (i.e. increasing the length of track) the complexity and size of the problem addressed increase and, the calculation requirements and the corresponding computer time as well. However, it is also possible that by increasing the number of sections, the possibility of producing movements that have major impact decreases, since the movements are more restricted by the lack of capacity available and so more iterations are required to find a lower cost solution.

Table II – Track length configurations, number of iterations performed and movements executed

Track length configurations	**No. of iterations performed**	**No. of executed movements**
260 km (26 sect.)	9768	4852
240 km (24 sect.)	7754	3904
220 km (22 sect.)	9069	3749
200 km (20 sect.)	7548	3124
180 km (18 sect.)	8518	2426
160 km (16 sect.)	8021	1359
140 km (14 sect.)	6931	813

Concerning the greatest reduction of the variable costs (operation and travel) obtained between the IBS and the lowest cost solution, it was found that the 180 km track configuration presents the greatest reduction with an around 40% decrease of variable costs. Thus, from the results obtained for this analysis, the conclusion that there are many possibilities of reconfiguring the schedule so as to obtain low cost solutions is derived. On the other hand, for the 260 km solution the respective reduction was only 10%.

Table III – Costs for IBS and costs for the minimum cost solution and respective reduction (variable costs are operational and travel costs)

Track length configurations	Variable costs for the IBS	Variable costs for the minimum costs solution	Reduction of the variable cost
260 km (26 sect.)	3222	2894	-10%
240 km (24 sect.)	3213	2489	-23%
220 km (22 sect.)	2888	2205	-24%
200 km (20 sect.)	2659	1733	-35%
180 km (18 sect.)	2570	1494	-42%
160 km (16 sect.)	2011	1288	-36%
140 km (14 sect.)	1825	1151	-37%

Concerning the epochs, it was found that the lowest cost solution ranges from the epoch 3 on the 140 km track configuration to the epoch 15 for the solution of the 180 km configuration, which was referred earlier as the most cost improving one.

Table IV – Epochs with the lowest cost solution, unitary for minimum cost solution (per section for the analysis period) and respective quality measures

Track length configurations	Unitary costs for minimum cost solutions	% of sections below QN1	% of sections between QN2 and QN1	% of sections between QN3 and QN2	Solution found at epoch/iteration
260 km (26 sect.)	207442€	51	28	21	6/2375
240 km (24 sect.)	207875€	47	27	26	11/4003
220 km (22 sect.)	213864€	48	28	24	6/2056
200 km (20 sect.)	211625€	45	27	28	9/3316
180 km (18 sect.)	221889€	44	25	30	15/5762
160 km (16 sect.)	236719€	44	26	30	5/1942
140 km (14 sect.)	260786€	44	15	30	3/1901

Regarding the maintenance cost per section which is the figure used to define the most effective length of track to be performed by one tamping machine, the lowest unitary cost solution found was for the 260 km length configuration. This value was expected, since it comprises of the highest number of sections and the fixed acquisition cost of the tamping machine is spread into many sections, leading to a low overall cost per section. However, the quality of the track delivered by this solution cannot be accepted, since around 20% of the track being between QN2 and QN3, which is solution that does not comply to the UIC recommendations and thus could not be accepted. This percentage of the track quantity that shows quality between QN2 and QN3 is faced as fundamental to evaluate a configuration solution, since it ensures the implementation of the safety criterion.

From all the track length configurations tested, the solution that presents the closest values to the UIC quality standards is the 220 km and 240 km track configurations. They also show the lowest maintenance cost per section 24489€/year and 23804€/year respectively. It is also worth noticing that solutions are obtained in the very beginning of the SA algorithm process, when the IBS is defined.

Table V – Unitary costs for minimum cost solution (per section for the analysis period) that accomplish the 10% QN2-QN3 levels

Track length configurations	Unitary costs for minimum cost solutions	% of sections below QN1	% of sections between QN2 and QN1	% of sections between QN3 and QN2	Solution found at epoch/iteration
260 km (26 sect.)	220058€	56	31	14	0/IBS
240 km (24 sect.)	238042€	58	34	8	0/IBS
220 km (22 sect.)	244886€	58	33	10	0/IBS
200 km (20 sect.)	255600€	61	29	10	1/166
180 km (18 sect.)	271139€	64	25	10	2/466
160 km (16 sect.)	278688€	61	29	10	1/204
140 km (14 sect.)	301786€	62	27	11	1/199

According to the criteria adopted in the methodology, and with the usage of the current values that were presented in the previous paragraphs, the solution to the problem addressed in this paper is the 240 km track length for two reasons; firstly because it respects the quality criteria set by UIC and secondly guarantees the lowest unitary maintenance cost. However, it has to be noted that the influence of the values adopted for each cost category is determinant to the maintenance unitary cost. Furthermore, by testing the model with a different acquisition cost for the machine (a lower value) the results are in favour of the small track length configuration.

CONCLUSIONS

This paper address the problem of calculating the effective length of track that could be maintained by a tamping machine and a methodological and computational approach was presented. Furthermore, a numerical application of the proposed model was performed. he model used the simulated annealing meta-heuristic to find a lower cost scheduling plan to accomplish - maintenance, while the optimization of the schedule plan has been conducted on the basis of the travel and operational costs of a tamping machine. The acquisition cost of the machine was added to the previous costs and a unitary maintenance cost was calculated for the sections of the track. Those costs were confronted with the quality level showed by the optimum schedules derived.

The implementation of the proposed simulated annealing model showed very interesting results, including significant cost reduction. The meta-heuristic was directed towards the maintenance cost reduction and evaluated with recommended track quality levels. The results of the model showed a deviation of the algorithm from quality standards towards lower cost maintenance solutions.

The methodological framework developed in this paper seems efficient in serving the objectives of the present work. Interesting modifications for the future extension of the model would be the inclusion in certain way the quality of the track, in the cost function to be assigned to SA. Finally, a more precise determination of the effective length of track that should be assigned to a tamping machine should focus on the operational level and incorporate a rigorous assessment algorithm of the permanent capacity of the tamping machine for each time period.

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