Optimal maintenance planning process

The Case Study of Metropolitano de Lisboa

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Abstract

Metropolitano de Lisboa (ML) is one of the main state-owned transportation companies that operates in the city of Lisbon, and besides its core function, can also perform maintenance tasks to their Rolling Stock. The struggling financial situation of the Portuguese state-owned transportation companies, created the opportunity to improve the proceedings and the maintenance tasks' efficiency and effectiveness, and the ML Maintenance Department, in this case, identified the maintenance planning and scheduling process as one of the areas to improve.

Therefore in the present paper, and based on the analysis of the current procedure and on the literature review on this topic, is presented a 2-stage methodology for the maintenance planning and scheduling procedure. In the first stage, the rolling-stock and the several tasks are sorted and pre-selected, being this set used on the second stage, where a Mixed Integer Linear Programming Model (MILP), based on the *Resource-Task Network* methodology (RTN), is used to schedule the several tasks on the employees' weekly timetable.

Finally, and together with several scenarios, the developed proceeding is applied to the problem identified by ML, being some conclusions drawn about its relevance and applicability.

Keywords: Efficiency improvement, Optimization, Operations' planning and scheduling, Resource-Task Network, Rolling Stock maintenance

1. Introduction

The public transportation systems play an important role in the economical and social development of the city where they operate, allowing an improvement of the social and living condition for those who use it. According to Murray et al. (1998), it is even possible to measure the importance of the use of public transportation by economical and environmental levels, as well in the welfare of its users.

In the Portuguese case, despite all the benefits produced by the transportation systems, the financial sustainability of the companies who provide this service is at stake, due to low investment returns and efficiency problems in their operation. The situation of ML and other railway companies is not different, being necessary to introduce changes in the proceedings and in the way that the service is fulfilled to the customer.

Kontaxi and Ricci (2010) state that, in the case of the railway companies, a way to reduce costs could be achieved by improving the resource utilization's efficiency, applying this concept to the rolling stock use, the work made by teams of employees and maintenance operations and proceedings. Carretero et al. (2003) state that the optimization of this process is one of the most important tasks to be performed.

The main goal of this paper, and for ML, is to obtain a methodology that allows the company to develop a maintenance task planning and scheduling based on mathematical optimization, in order to improve resource and facility utilization. Since this is something that is not done currently on the company, the goal to spend capital on a wise and efficient manner, motivates the present work. So, the paper is structured as follows: in Section 2 the literature about maintenance planning and tasks scheduling methodologies is reviewed; in Section 3 the problem is present, as well some of its characteristics and particularities; in Section 4 the methodology created is presented; and the same is applied to the Case Study in the Section 5, where several scenarios also tested to evaluate the methodology's performance and applicability; finally in Section 6 some conclusions are drawn.

2. Literature Review

2.1. Maintenance Task Planning and Scheduling

The maintenance planning and scheduling process consists on the combination and availability of six main factors: number of human resources, tools, parts, equipment that requires maintenance, data about the task to be performed and permission to this occurrence (Garg and Deshmukh, 2006).

In the Literature, it is possible to find different types of methods that could be used to perform the activities of planning and scheduling, but it is possible to split them into two groups, stochastic and deterministic methods. Due to the characteristics of the Case Study, we will only revise the deterministic methods.

In the Transportation sector there are few references related to this subject, Sriskandarajah et al. (1998) developed a methodology for the Mass Transit Railway Corporation of Hong Kong that was based on Linear Programming and Genetic Algortihms and Haghani and Shafahi (2002) present a procedure, also based in Linear Programming, to improve the planning process in a Bus transportation company by maximing the number of buses called to perform maintenance, and minimizing the number of cars, on duty, that need maintenance (taking in consideration the number of resources available). In other sectors of activity, it is possible to refer the work made by Yao et al. (2001), that developed a Linear Programming model to produce a short-term planning of maintenance activities in a Semiconductors Plant and Joo (2009) who proposed a model to optimize the maintenance scheduling of modular components.

2.2. Scheduling of generic tasks

Planning and scheduling are two concepts that, despite having different purposes and applications, are very important for the function of the organizations. While planning is more focused on the long term, the scheduling is related to the short term decisions, such as resource allocation to activities and also the determination of each activity's beginning (Langevin and Riopel, 2005; Leung, 2004).

In the scheduling related problems/modelling, it is possible to differentiate several types of goals and methodologies. In terms of goals, the most common objectives could be related with the makespan (Leung, 2004), the total completion time of the activities (Leung, 2004) or even with the lateness or tardiness of the several scheduled activities, that could be made in one, two or more-non parallel and two or more – parallel machines (Pinedo, 2008).

Despite the possibility to combine different types of objectives with different number of machines, some types of problems could be very hard to model due to their constraints. For this purpose, and taking in consideration the type of problems constrained by the availability of resources, workplaces or parts (where the present case study is included), it is possible to refer two methodologies related to this situation: the State-Task Network (STN) and the Resource-Task Network (RTN). Both methodologies use a graph, in order to represent the relationship and also the sequence (if exists) between the several stages of a process.

In the case of STN, the basis of the model is on the state change of the activities, where is possible to know, for each moment, if a certain equipment is in use or not (Kondili et al., 1993), but it fails in the consideration of the amount of resources used /produced in the stages, being that the main difference to the RTN methodology (Pantelides, 1994). These methodologies allow the creation of different types of models. Méndez et al. (2006) present a review of each type of modelling procedure that could be used and, in each case, are presented the critical aspects that should be taken in consideration.

3. Case Study

As mentioned previously, the main goal of this paper is related with the optimization of the maintenance scheduling process used by ML, allowing the company to use efficiently and effectively their resources.

Metro de Lisboa possesses a fleet of roiling stock formed by 113 trains (including those who had crashes and are unutilized) formed, each one of them, by three carriages, and two workplaces to perform maintenance tasks to all fleet, one in Calvanas (PMO II – in the municipality of Lisbon) and another in Pontinha (PMO III – in the municipality of Odivelas). A train could go to one of these places due to two main reasons: to perform Corrective Maintenance (CM) or to perform Preventive Maintenance (PM). The improvement of the planning of the PM is the main objective, because their occurrence is determined by the number of kilometres that have passed since the last maintenance and that also because the occurrence of CM is impossible to plan, due to its unpredictability (they only occur due to breakdowns).

There are about 40 types of PM that could performed in each train, each one of them with different characteristics, such as the duration, the workforce required to perform it, the workplaces, in each PMO, where it could be performed, etc. It is important also to highlight that these PM tasks could be divided into three groups: Train inspections (TI - more general tasks, that include cleaning or general inspections to some components of the train), Component interventions (CI - more specific tasks, specially designed to avoid breakdowns in several parts – in the short term) and Improvement tasks (IT - developed to improve the safety levels and to avoid breakdowns – in the long term). In the present paper, the IT tasks will not be considered.

In the case of TI and CI tasks, the main factors that characterize them, and define their occurrence, are: the number of kilometres that have passed since the last maintenance; the interval of kilometres, around the exact moment of execution of the task, that define the most suitable moments to perform it (tolerance of each task); the number of kilometres that should be ran between executions of the same task, and also the number of resources required to perform them (workforce and parts).

Currently, the process of planning maintenance activities, could be explained by a number of steps, presented in Figure 1, for each of the PMOs of ML.

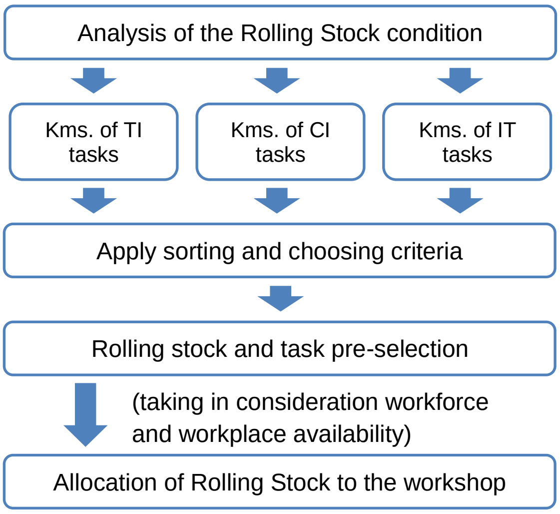

Figure 1 – Process of maintenance planning, currently in use at Metropolitano de Lisboa

Most of the steps and routines presented are based on heuristic proceedures developed by the team of workers of ML. Therefore, and relating the presented proceeding to the objetive of this paper, the main goal is to replicate the several criteria and routines used by Metro, in order to obtain a planning and a schedule metodology that could minimize the dependence on those heuristics, and also to improve the efficency in the allocation of tasks to the available workforce.

4. Planning and Scheduling Methodology

The solution developed for the problem described in the case study, is a 2-phase methodology that intents to produce a list of trains and tasks to be performed, sorted by its relevance and by the need of maintenance (in the first phase), and then produce work timetable plans, that should ensure the scheduling of the largest number of tasks (second phase). The reason of defining, as goal, the scheduling of the largest number of tasks is related with the desired efficiency improvement. In this case, was decided if more tasks could be scheduled there would be less unoccupied workers, and so the efficiency on the allocation of workers to the tasks would rise. Therefore, in the Figure 2, are presented the main stages and steps that characterize the methodology developed, for each PMO, and that would be described in the following sections.

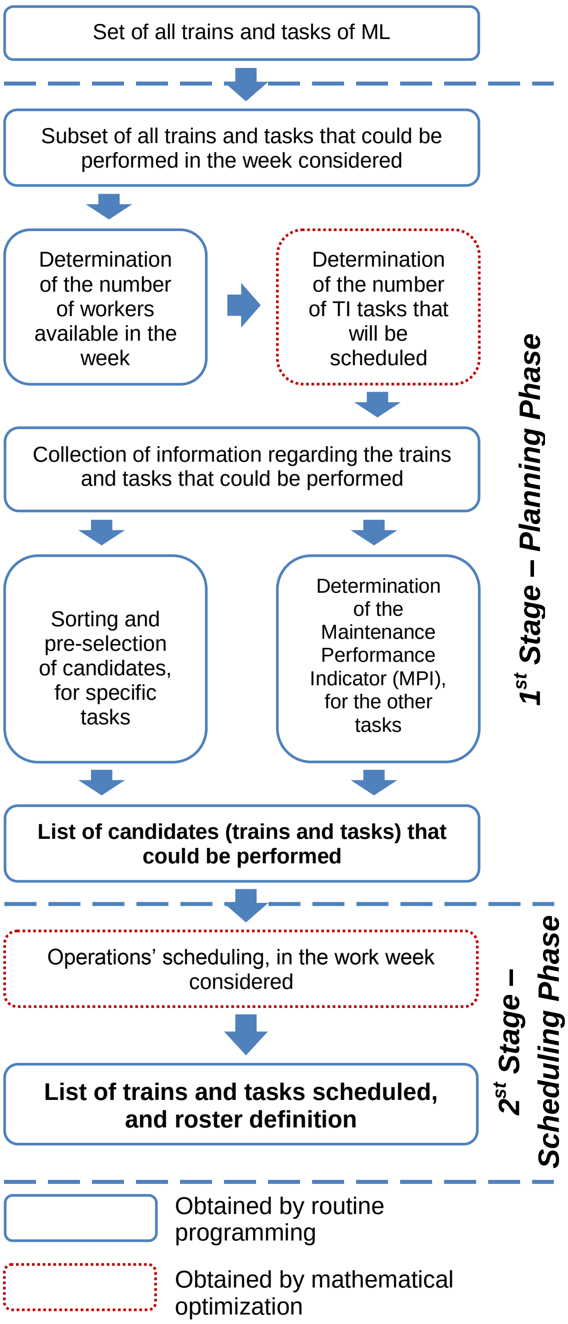

Figure 2 – Steps of the methodology created for the Case Study, to be applied in each PMO

The programming of the routines used was possible with the use of *Microsoft Excel's* programming capacity (using *Visual Basic for Applications* language) and the mathematical models were develop with the compiler *GAMS* (*General Algebraic Modelling System*).

4.1. First Stage – Planning Phase

The first stage of the methodology developed intents to replicate the process of choosing and pre-select trains and tasks to be performed. The main difference between this methodology and the case study, is that in this case the complete list of possibilities should be formulated before the beginning of the second stage, but in the real case the list could be changed, because there was a real-time listing of the number of man-hours still available, to perform maintenance tasks.

4.1.1. Subset of trains and tasks that could be performed

This first step of this stage intents to develop a list of trains and tasks that could accomplished during the time horizon defined. It is important to develop this step because there are several trains that could not be called to perform maintenance (due to breakdowns or accidents) and several tasks that could not be accomplished (due, for example, to the lack of the parts needed to execute the job).

4.1.2. Determination of the number of TI tasks that will be scheduled

The execution of most part of the TI tasks is regulated by contract, because most of them are subcontracted to other companies (for example, the cleaning tasks are one of those included in this group) and some have a required number of executions per week.

For these reasons, and taking in consideration the number of workers available along the week, a Mixed-Integer Linear Programming Model (MILP) was formulated to determine the optimal number of TI tasks to be performed. The model was developed under the RTN methodology, whose objective was to maximize the number of IT tasks to be performed along the week, as can be seen in the Equation [1].

- ***Objective function (1st Stage)***

$$Max\ Z = \sum_{ut \in UT} \sum_{j \in rutint_{ut,j}} \sum_{t \in taskstart_{j,t}} \sum_{r \in rec_{j,r}} x_{ut,j,t,r} \quad [1]$$

- ***Indices***

ut – trains
j – tasks to be performed
t – time units
r – type of utilization of human resources

- ***Sets***

$UT = \{ut_1, ut_2, \ldots, ut, \ldots, ut_N\}$ – set of trains that will be scheduled. In fact these are not real ML trains, because the only purpose of using this terminology is to allocate the TI tasks, being each one of them related to fictional train. Each one of this, can only perform one task.

$rutint_{ut,j}$ – set of tasks that could be scheduled to each considered train

$taskstart_{j,t}$ – set of time units defined for the beginning of each type of task

$rec_{j,r}$ – set of all possibilities of utilization of human resources for each TI task.

- ***Variable***

$x_{ut,j,t,r}$ - allocation variable, that is equal to 1 if the task j to be performed by train ut, is scheduled on time t using the type r of human resources' utilization, defined for that task

The model includes several types of constraints so as to replicate the criteria used by Metro to schedule these type of tasks. The following list represents some of the constraints used in this mathematical model:

- the maximum number of TI tasks, of each type, that could be scheduled during the time horizon (and in each PMO);
- the maximum number of parallel executions, of the same type of task;
- task-sequence rules;
- the number of human resources available, in each period of the time horizon
- and the maximum duration allowed for the different tasks.

The output of this problem, the number of tasks that could be scheduled in the time horizon defined, will be used to define the combination of trains and tasks that most need to perform each one of the TI tasks defined.

4.1.3. Collection of information and determination of the MPI for each task

Before advancing to the final selection of all trains and tasks that could be performed, in each facility, it is necessary to collect all the relevant data for this procedure. The most important data required to perform the selection of all candidates are the number of kilometres that have passed since the last execution of each one of its tasks and the tolerance defined for each type of task. For some tasks, such as the case of the TI tasks, the number of kilometres is the only indicator needed to sort and pre-select the tasks and trains to be schedule.

But in the most CI tasks considered in this case, the consideration of the number of kilometres ran since the last execution of the task, is not enough to decide which task will be performed. For example, if a train has the same distance covered for two different tasks, it is necessary to define an indicator that could say which one of them will be executed.

For these cases an indicator was developed, named the Maintenance Performance Indicator (MPI), that intents to measure if a certain task as an higher priority in its execution, rather than other. This indicator intends to give this information by measuring the relative difference between the number of remaining kilometres, that a train has to cover, and the exact moment of the task execution, but taking in consideration the tolerance defined for that specific task. As referred previously, the tolerance defined for each task is the interval of kilometres, around the optimal moment of execution of the task (when the remaining distance, between executions of the task is equal to zero km), that is more suitable to perform its execution (in most cases, it is impossible to schedule the execution of a task with its ideal moment to be performed).

To better understand this indicator, an example of its use is presented in Table 1.

Table 1 – Determination of MPI for two tasks, of the same fictional train

Task	***Remaining Kms (optimal moment)***	***Tolerance (Kms)***	***MPI***
Task 1	5 000	10 000	0,5
Task 2	5 000	2 500	2

In this case, both tasks have the number of remaining kilometres, but as it is possible to see, the Task 1 could be performed rather that the Task 2, because in the first case the number of remaining kilometres of the task is lower than its tolerance (making the MPI indicator lower than one). The MPI indicator also allows to read that, in the first case, the train is on the middle of its tolerance (50% of the distance defined, could still be ran, until the optimal moment of execution of the activity).

4.1.4. Sorting and pre-selection of candidates, for specific tasks

The execution of some types of maintenance tasks, apart of being dependent of the number of kilometres ran since the last maintenance, are also related with the execution of other tasks.

In the case of Metropolitano de Lisboa, due to the characteristics of some parts' utilization, these require the existence of more than one type of task to ensure their safe utilization. For example, in the case of the Batteries used in the trains, there are two types of tasks that could be performed: one of them, with reduced distance between executions, ensures that fluid levels are okay, and the other, with larger distances, performs a full verification of the state of the Battery.

Based on this case, and taking in consideration that the unique information available about the tasks – the number of remaining kilometres, in some cases it's difficult to choose whose task will be scheduled.

For this reason, the present methodology contains a series of routines that determine, for each train, which task is more suitable to be performed, based on the comparison between tasks related to the same part.

4.1.5. List of candidates (trains and tasks) that could be performed

Taking in consideration the several routines and criteria used to sort the several tasks, by their relevance and need to perform maintenance, the present step intents to develop a final list of candidates (trains and tasks) that could be performed, during the time horizon defined and for each PMO.

For the case of the TI Tasks, due to the fact that is possible to know how many tasks, of each type, will be scheduled during the workweek, the routines above described could define which trains will be called to perform these same tasks.

For these selected trains, and in order to justify their presence at the workshop, the present methodology should try to allocate as many tasks as possible (only if the condition of those tasks allows their execution – number of kilometres near their optimal point of execution), in order to seize all the opportunities for their execution, during the time that the train will be immobilized.

For all the trains in these conditions (scheduled to perform TI tasks), all the other tasks that meet the criteria for being perform, will be taken in consideration, and sorted based on their MPI and other routines defined. For the other trains that will not perform TI tasks, the same analysis will be made, but their occurrence will be dependent on the execution of all the possibilities identified previously.

4.2. Second Stage – Scheduling Phase

In this second stage, a mathematical optimization model will attempt to schedule the larger number of tasks, in the time horizon defined. To do so, the present stage is based on the list of trains and tasks that could be schedule, in each one of the PMO, but also in a number of restrictions and conditions that should be taken in consideration. The objective of this stage is to obtain a schedule, for each PMO, that considers the largest possible number of tasks scheduled.

4.2.1. Mathematical model

In order to achieve the goal of scheduling the largest number of maintenance task, a mathematical model was formulated based on the RTN methodology developed by Pantelides (1994) and Méndez et al. (2006). The reason why this methodology was used is related to the fact that it is possible to adapt it to several types of scheduling problems, the several resources used in the problem could be easily managed and also the fact that, due to the simple formulation used, it consumes less computational resources.

In practical terms, the current mathematical model will have the goal to schedule the larger number of maintenance tasks in the PMO in consideration. But, and as the information of how many TI tasks will be allocated in the time horizon defined is known, this model will only account the number of optional tasks (all the ones, except the TI tasks that will occur) that will be scheduled.

Having known the list of trains and tasks that are candidates to be scheduled, the development of present model is mainly based in the following information:

- the time horizon defined for the operations' scheduling (in this case will be one week, in each facility);
- the characteristics of each task, such as its duration, the number of human resources required to perform it, the workplaces where the task could be performed and the time moments at where the task could be initiated;
- the maximum number of workplaces that each train could occupy, during his stay on the facility;
- the number of workplaces and human resources available.

But, due to the several operational characteristics of this problem, some of them could not be included in the formulation of this model. The model's performance and the fact that some ML constraints are very difficult to be represented, the following list of assumptions was established:

- as refered, it will be taken in consideration a division between mandatory tasks to be performed (TI tasks) and optional tasks (all the other tasks - but the tasks that could be performed by trains that will be immobilized in the period, have an higher priority to perform those);
- each time period has the duration of one hour;
- each train, could not perform two different tasks simultaneously;
- all the tasks (with the exception of one type of TI task) should be ended until the end of the day, when there were initiated;
- when a train is allocated to a workplace, it will only leave the place when all the tasks, that could be executed there, have been completed;
- some tasks, that are composed by several subtasks, have a maximum time duration to be performed;
- each train should occupy the minimal number of workplaces in the facility.

Regarding this last topic was developed an Algorithm whose objective is to return, for a certain train and set of possible tasks, the maximum number of workplaces that should be occupied (Figure 3).

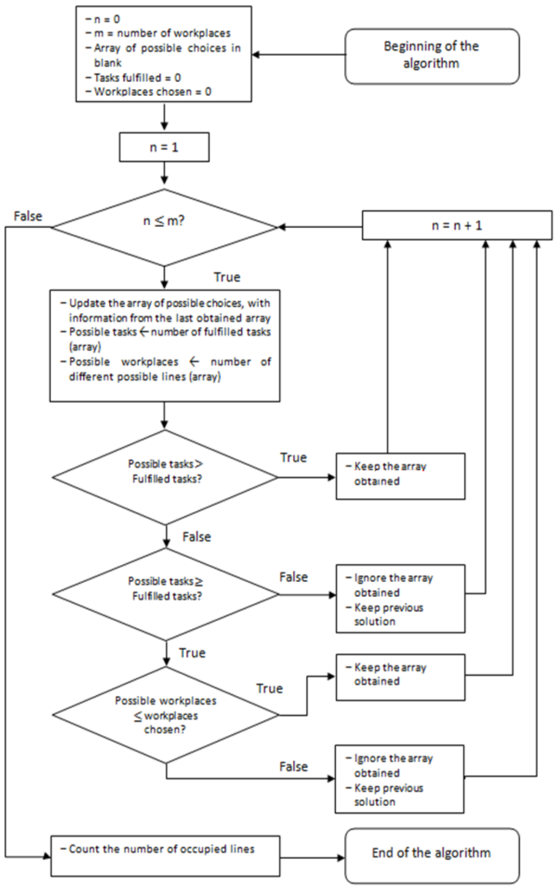

Figure 3 – Algorithm for determing the maximum number of workplaces, that a train could occupy

So, and in order the meet the objective stated, expression [2] represents the objective function defined for this particular model.

- ***Objective function (2nd Stage)***

$$Max\ Z = \sum_{ut \in UT} \sum_{j \in option_{ut,j}} \sum_{m \in tasklines_{j,m}} \sum_{t \in taskstart_{j,t}} \sum_{r \in rec_{j,r}} x_{ut,j,m,t,r} \quad [2]$$

- ***Indices***

ut – trains
j – tasks to be scheduled
m – workplace
t – time units
r – type of utilization of human resources

- ***Sets***

$UT = \{ut_1, ut_2, \ldots, ut, \ldots, ut_N\}$ – set of trains that will be scheduled

$option_{ut,j}$ – set of optional tasks that could be scheduled to each considered train

$tasklines_{j,m}$ – set of possible workplaces where the task j could be performed

$taskstart_{j,t}$ – set of time units defined for the beginning of each type of task

$rec_{j,r}$ – set of all possibilities of utilization of human resources for each task.

- ***Variable***

$x_{ut,j,m,t,r}$ - allocation variable that is equal to 1 if the task j to be performed by the train ut, is scheduled on time t, and in the workplace m, using the type r of human resources' utilization, defined for the task.

The type of constraints used on this formulation intent to replicate the larger possible number of real constraints applied at Metro, in order to obtain the most real and adequate output possible. The main constraints covered by this model are related to the following topics:

- the maximum number of tasks, of the same type, that can start simultaneously;
- the sequences defined for the allocation of the different jobs (to remember that the allocation of optional tasks should respect the ranking defined on the previous stage);
- the management of the use of workplaces, workers, and number of jobs in execution for each period of the time horizon;
- the number of trains present, for each day of the week in consideration, at the facility (ML defined a daily limit for this parameter – in order to not compromise the core function of the company – passenger transportation);
- and task-sequence restrictions.

Finally, after the execution of the model for each facility, it is possible to obtain the final list of and the schedule of activities to perform, during the time horizon considered.

5. Results

In order to test the methodology developed, a set of data and results from a particular workweek were used and three scenarios were also tested, for each PMO:

- Scenario 1 – direct utilization of data from ML (in order to compare with real results)
- Scenario 2 –workers' strike
- Scenario 3 – workplace unavailable

All these scenarios were based on the information obtained from Metro, that was used to schedule maintenance tasks in the week of 8 to the 14 of September of 2014. The second stage of the methodology was limited to 10 hours of computation.

In this particular week the results contained in the Table 2 were obtained.

Table 2 – Results of the real case

	PMO II	***PMO III***
Man-hours available	575	394
Man-hours used	411,5	194
N. of workplaces available	8	12
N. of TI tasks performed	45	25
N. of other tasks performed	17	8
N. of trains scheduled	46	22

5.1. Scenario 1

For this first scenario, the results present on Table 3 were obtained.

Table 3 – Results of Scenario 1

	PMO II	***PMO III***
Man-hours available	570	316
Man-hours used	386	120
N. of workplaces available	8	12
N. of TI tasks performed	46	25
N. of other tasks to allocate	67	36
N. of other tasks performed	30	16
N. of trains scheduled	42	23
Relative Gap	123.3%	87.5%
Computational time (s)	36 000	333.8

In this case, it is possible to see that the number of tasks scheduled increased in both cases, comparing with the real, but it is interesting to note that the number of man-hours used decreased in both cases. This fact has two justifications:

- First, there are some tasks that, despite being scheduled on the real case, due to their characteristics, the proposed methodology could not consider;
- Second, some tasks, namely the TI tasks that are subcontracted, usually need to be performed by ML workers, but if they are not available, they are still executed. For these cases the two possibilities were took in consideration, and the model in most cases preferred to use the option with no ML workers needed.

5.2. Scenario 2

The second scenario intents to represent the case, that in one of the week days the workers are on strike (for all day – and in this case a Wednesday). The results obtained are present in Table 4.

Table 4 – Results of Scenario 2

	PMO II	***PMO III***
Man-hours available	458	245
Man-hours used	343	106
N. of workplaces available	8	12
N. of TI tasks performed	45	24
N. of other tasks to allocate	67	36
N. of other tasks performed	39	16
N. of trains scheduled	41	23
Optimal Gap	71,8%	125%
Execution time (sec)	36 000	370,8

Curiously, the number of tasks scheduled was higher when compared to the real case. One of the reasons for this situation is due to an decrease on the number of TI tasks allocated, and some of these tasks are known to have large durations and need of workers.

5.3. Scenario 3

The final scenario, as stated, intents to test the case where one workplace is unavailable (in this case, a workplace that could perform the larger number of tasks). The results presented on Table 5.

Table 5 – Results of Scenario 3

	PMO II	***PMO III***
Man-hours available	570	316
Man-hours used	308	126
N. of workplaces available	7	11
N. of TI tasks performed	76	25
N. of other tasks to allocate	67	36
N. of other tasks performed	14	16
N. of trains scheduled	42	23
Relative Gap	378.6%	125%
Computational time (s)	36 000	636.56

In this case it is possible to analyse that the unavailability of a workplace will decrease the capacity of scheduling tasks at PMO II, rather than PMO III.

5.4. Sensitivity Analysis

In parallel with the previous analysis, a sensitivity analysis was also performed to one particular parameter, the number of workers available. Since the week in study, was a week where many workers were on holidays, the analysis that was carried on only considered a positive difference in this parameter, respectively more 1, more 2 and more 5 workers in every time moment, when compared to the real case.

The main conclusions that could be taken from this analysis is that with just one more worker, at every moment in PMO III, would be possible to perform all the tasks in the candidates list. Meanwhile, in the case of PMO II, with one more worker would be possible to schedule 3 more tasks, but the analysis stopped at this point, because the methodology were not able to give results before reaching the time limit of the execution.

6. Conclusions

In this paper was presented a methodology that was created to improve the planning and scheduling of maintenance tasks at Metropolitano de Lisboa.

The methodology created was composed by two steps, each one representing the objectives above referred, and was constituted by several routines and procedures (for instance, to define which tasks would be performed and which trains would be called to each one of the facilities, to perform them), but also a set of mathematical optimization models, based on the *Resource-Task Network* methodology. Those models have the objective of facilitating the task of scheduling the several proposed tasks, through the allocation of the larger number possible of tasks, in the time horizon defined but as well taking in consideration the several constraints and limitations of this process.

As future work is suggested some developments: improve the MILP model, in order to increase its performance and decrease its execution time namely when applied to PMO II; adapt the methodology to accommodate the tasks that were not considered; and finally develop routines and procedures to take in consideration the IT tasks.

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