Compliance of maintenance and operational needs for trains: a simulation analysis to evaluate the impact of a flexible scheduling on local transport by rail

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M. Agostino, C. Caballini, B. Dalla Chiara, P.G. La Scala

Abstract— **If not properly managed neither planned on real needs, the maintenance of rolling stock may strongly affect rail operations in local public transport, risking to compromise the quality of service or generating an over sizing of the fleet. Therefore, an effective coordination is required between the Operation and Maintenance departments. Some flexibility in maintenance activities i.e., preventive and on condition maintenance policies - has already been applied for some years in the regional rail transport with successful results; however, it has not been introduced yet in rail public transport, where a corrective maintenance is generally adopted. In this work, the proper scheduling of more flexible maintenance activities in the rail public transport context is addressed through the use of discrete event simulation. Real data sets provided by the Italian GTT-Gruppo Torinese Trasporti company have been used to test the proposed approach and to carry out a multi-scenarios campaign, aiming at analyzing the effectiveness of the maintenance process when certain operating conditions change or unexpected events occur. Some improvement proposals have also been analyzed with the proposed simulation method.**

I. Introduction

As all machines used by companies to guarantee the production or service, rolling stock also needs maintenance. The maintenance activity is aimed at avoiding the onset of breakdowns, ensuring the regularity of operation and the trip safety, guaranteeing an adequate level of comfort for passengers, extending rolling stock life and minimizing total maintenance costs (management of resources, the used material and the involved personnel) [1], [2]. In order to pursue these objectives, maintenance activities must be planned with high effectiveness and efficiency [3]. There are several studies in the literature concerning maintenance activities that differ according to the pursued objectives: the reduction of train travel times [4], the optimization of traveling staff allocation [5] or the minimization of totals costs over a certain time horizon [6], [7]. Since maintenance plays a crucial role in relation to the useful life of a component, for some years now the parameters related to components Reliability, Availability and Maintainability (RAM) must be provided in the purchase phase, with the aim of giving indications about optimal management of the maintenance , so minimizing the component Life Cycle Cost (LCC) [8]. In particular, reliability refers to the probability that the system operates in the ways established for a given period, availability concerns the probability that the component is able to perform predetermined functions once it carried out the appropriate maintenance interventions, and maintainability indicates the probability that the maintenance action can be performed at pre-established intervals. RAM parameters provide a railway company with precise indications on maintenance plans which, if properly respected (in terms of times and methods), guarantee the maximization of the useful life and performance of the rolling stock [9]. In order to perform the correct maintenance on all the rolling stock available, the railway company must have a general plan of the interventions to be carried out and properly schedule the rolling stock turnaround time (i.e., the allocation of the rolling stock to train travel) in such a way to be respected by this plan.

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In some local rail transport companies, corrective maintenance has been recently substituted by preventive maintenance, which is based on the replacement or overhaul of still functional components, with the aim of decreasing the probability of uncontrolled failure of the component and having as little stoppage as possible of the rolling stock. The rolling stock wear essentially depends on two factors operating simultaneously: the operating time and the resistance of the railway infrastructure to the train motion. The spacing of maintenance is therefore conceived on the basis of temporal criteria (Mean Time Between Failure - MTBF) or operation contexts (Mean Distance Between Failure - MDBF) [10]. Numerous studies highlight the potential and critical issues of these approaches both in the railway sector [11], [12], [13] and in the perspective of a more general maintenance vision [14], [15].

In addition, alongside or in replacement of the preventive maintenance above described, maintenance on condition is increasingly spreading. This latter is based on the evolution analysis of the actual state of a component thanks to the monitoring carried out through some measurements (visual checks and not destructive tests) without the need of disassembling the the rolling stock parts [16]. With this type of maintenance, the idea of timing maintenance is abandoned and the possibility of basing maintenance on the real health condition of the component is introduced [17], [18]. This maintenance philosophy has undoubted advantages on the economic and operational aspects, and also plays a key role in the design of the rolling stock since the vehicle must be equipped with a series of tools to guarantee the monitoring of its wear over time.

Another aspect to consider is the relationship between the number of maintenance interventions and the continuity of the operation [19]. In fact, the rolling stock is composed of numerous components that operate simultaneously to ensure the motion of the train. However, the wear of these components is not simultaneous but differentiated over time based on the operating conditions. The strict fulfilment of the maintenance of each component without considering the other components needs may lead to a very high number of rolling stock stoppages and, thus, invalidate the level of service guaranteed to passengers. It is therefore necessary to find a balance between these two aspects, accepting different tolerances in terms of wear of the individual components and, hence, grouping as many interventions as possible in the same maintenance machine down [20].

The goal of this work is to effectively plan the rolling stock maintenance (and, therefore, its stop in the workshop) in order to meet the needs of operation. To this end, a simulation model has been implemented (using the Arena software properly interfaced with some worksheets), capable of carrying out *what-if* scenarios and studying the effect of investment policies and unexpected events on operational planning and railway maintenance. In particular, a preventive evaluation of unexpected scenarios permits to adopt more effective strategies in case of their occurrence, trying to minimize possible negative impacts and making the whole system more resilient.

The proposed model was tested using the actual data and information provided by GTT-Gruppo Torinese Trasporti company, that provides the local railway service in the Italian city of Turin. In particular, utilizing the companies data, a multi-scenarios campaign has been performed, aimed at simulating and analyzing, through appropriate KPIs, the effectiveness of the maintenance process when certain operating conditions change or unexpected events occur; some proposals for the system improvement have also been studied with the proposed simulation framework.

In must be pointed out that discrete event simulation has been already used in the context of rail maintenance, such as in [21]) but in a short-term perspective on single occurring events. In fact, as in [22], this work focuses the attention on longer-term maintenance planning, seeking to involve the needs of all stakeholders in this organization.

The remainder of the paper is structured as follows. In Section II, the problem addressed in the paper is presented, whereas in Section III the analyzed processes and the implemented simulation model are described in more detail. Section IV presents the results of a multi-scenario simulation campaign and the related KPIs used to evaluate each scenario. Finally, in Section V some conclusions are outlined.

II. Problem Description

The problem addressed in this work deals with the analysis and simulation of the maintenance scheduling processes related to passenger rail transport, with the goal of minimizing downtime and maintenance costs. Constraints dictated both by the Operation and Maintenance departments are considered: the former defines train timetables and plans their compositions (i.e., the number and type of passenger wagons needed to satisfy the travel demand). The Maintenance department, on the other hand, thanks also to the specifications provided by rolling stock manufacturers, provides the deadlines within which maintenance interventions must be carried out.

Figure 1 shows the processes applied to schedule and perform preventive maintenance activities; the dashed red arrows indicate the synchronization between the two process flows. Moreover, the hatched rectangles indicate the activities implemented and managed by the Arena simulation model, while the non-hatched activities are managed by some calculation spreadsheets.

As shown in Figure 1, the Operation department first defines the train composition and calculates the accumulated mileage for each train. This information is passed to the Maintenance department, which therefore plans the related maintenance activities, organizing the movements and setting up the calendar. While the rail transport service is executed, the mileage is monitored by the Operation department and, once reached the scheduled thresholds, the train is sent to the workshop in order to execute the scheduled maintenance.

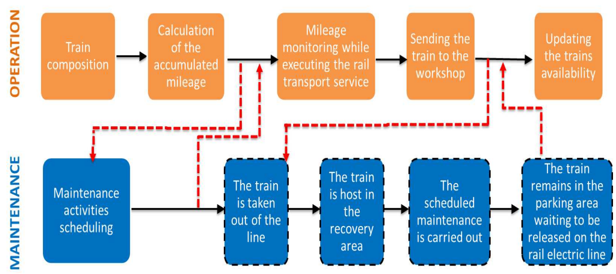

Fig. 1. Operation and maintenance processes and related inter-relations

The rolling stock maintenance activities are carried out in workshops located in special maintenance centers connected to the railway line, and typically near large train stations or terminals. In these centers different spaces used for specific tasks may be distinguish (Figure 2):

- *workshop provided with some maintenance ways*, i.e., specific tracks inside the workshop used to carry out the maintenance work. Typically, they are equipped with a pit for the inspection under the wagons and a bridge crane for the activities to be performed above them;
- *recovery area*, i.e., spaces typically located in front of the maintenance workshop in which the trains that must carry out maintenance (i.e., not suitable for the service) are stationed, waiting for the availability of a maintenance way;
- *parking area*, where the wagon/train available for the operation (i.e., those that have completed maintenance activities) can wait in order to go on-line.

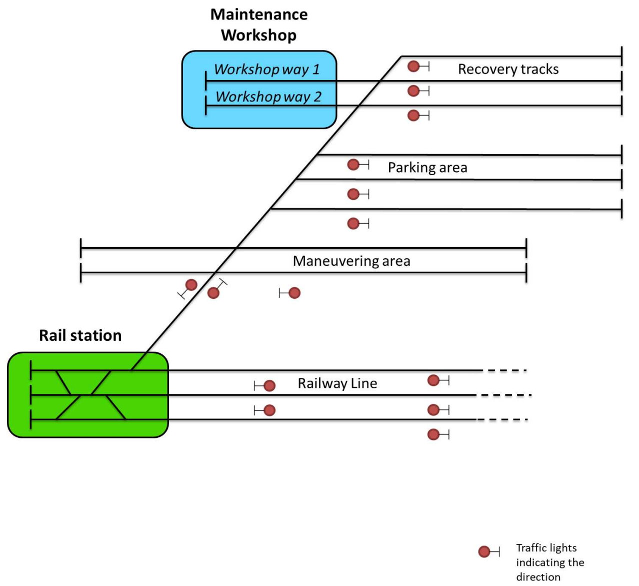

Fig. 2. Diagram of the areas available to a railway company for maintenance purposes

The rolling stock turnaround time is designed trying to pursue the following objectives:

- guarantee the scheduled train compositions;
- assign to each train the distance travelled in order to mature the mileage after which to perform the maintenance;
- always have sufficient wagons/train available in the parking area to meet any need for rolling stock replacement;
- minimize the stop time of trains;
- promote a fair distribution of the workshop workload over the considered time period, eventually anticipating/postponing the stoppage of trains in compliance with the constraints.

The spaces and resources available to the railway company must be managed in the best possible way both in order to minimize the wagons/trains shunting operations (which are time and personnel consuming) and minimize maintenance costs.

The time spent in the workshop is depending on the available resources (both human operators and machinery) and have some degree of uncertainty due to the real condition of the rolling stock that are verified at the moment; therefore, in order to reduce uncertainty, the train maintenance time needed is evaluated in day slot and not in hours, so to be sure to complete the maintenance. The time spent by wagons/trains in the recovery area must be minimized, as it is an unproductive time.

Figure 3 describes the cycle to which a train/convoy is periodically subjected: once the scheduled maintenance period has expired, the train is suspended from service and taken to the recovery area pending the execution of maintenance activities in the workshop. Once these activities are carried out, the train is brought to the parking area, ready for a new operating cycle.

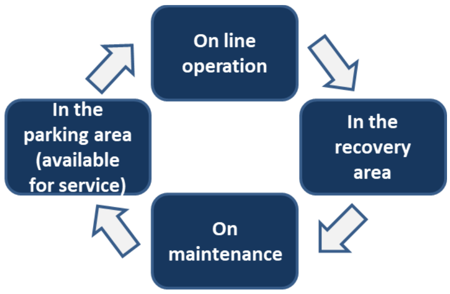

Fig. 3. Ordinary organization of the rolling stock turnaround time

In addition to the aspects and constraints described above, possible unexpected events that may cause changes in the maintenance planning should be taken into account. The most frequent events that the company has to face with are delays in maintenance operations and failures occurring during the rail service. While the former are partially absorbed by the tolerances adopted for the scheduled maintenance activities and thanks to the precautions already described in the planning of the rolling stock turnaround time, the latter involve a more complex procedure, described in Figure 4.

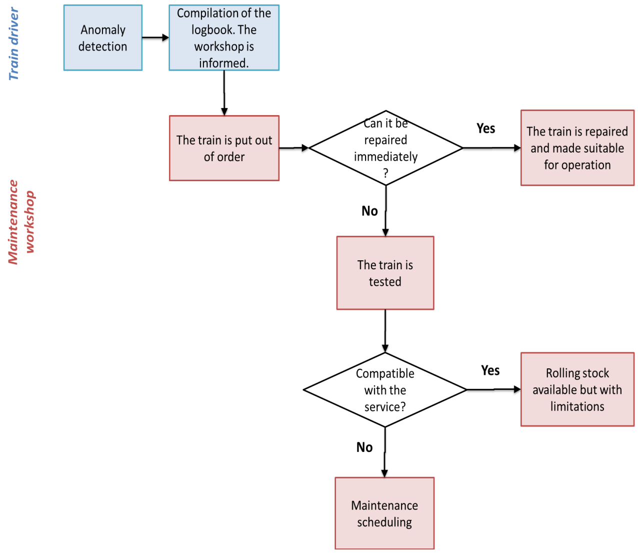

Fig. 4. Management process of an unexpected event

As shown in Figure 4, the train driver reveals the anomaly, updates the logbook and informs the workshop. The latter certifies the putting out of service of the rolling stock and decides whether to immediately carry out the repair based on the seriousness of the detected anomaly. If the repair can be carried out immediately, the rolling stock is soon available for the operation, otherwise further checks are carried out to better understand the problem and how to operate to fix it. With the new data obtained, the workshop can insert the train between the planned interventions to be performed or impose some limitations to its operation. The rolling stock is jointly produced by the Operation and Maintenance departments and periodically updated. Based on the number and type of rolling stock available, the Operation department chooses the train compositions to be made. It is therefore clear how the two departments must operate in synergy and respect mutual needs.

III. Simulation model

This section describes the discrete event simulation model developed to simulate the maintenance process over a certain time period. The model was implemented by using the Arena software, interfaced with a spreadsheet providing the maintenance workload in accordance with the scheduled provided by scheduled rolling stock turnaround time.

The Arena software reads the planned activities and creates a Train Card for each entity with the following information: the train unique identification and the company to which it belongs, the expected date of entry into the workshop, any recovery period and the theoretical date of the train release after having performed the maintenance Each card is assigned a specific entity in the software that runs through its simulation path and updates its status when the work is carried out.

After generating an entity, the Arena software initially checks whether the entry date corresponds to the internal date of the simulation; if so, it sends the entity to the first planned activity to which the respective duration has been attributed. Every day the generated entities make increase the processing times and are routed to different processes according to what they are supposed to do (Figure 5). More specifically, the possible alternatives are:

- *the maintenance area*: the entity is directed to the first free maintenance resource for being processed, taking into consideration possible specializations of the maintenance ways;
- *the recovery area:* if no resources in the maintenance area are free, the entity waits in one of the resources provided for recovery until a maintenance way is released;
- *the parking area*: once executed the scheduled maintenance, the entity is released and again available for the operation.

After its execution, the simulation software stores the parameters related to each train and the corresponding activities; in particular, for each wagon/train, the times elapsed from the entry to the exit of the model, the sequence and times spent on each occupied resource and any planning errors are recorded.

The structure of the implemented model, including the connections between its different parts, is provided in Figure 5.

IV. Multi-scenario campaign

In order to demonstrate the effectiveness of the proposed simulation approach, a multi-scenario campaign has been carried out using the real data provided by GTT company. The company acts as railway transport operator on some rail

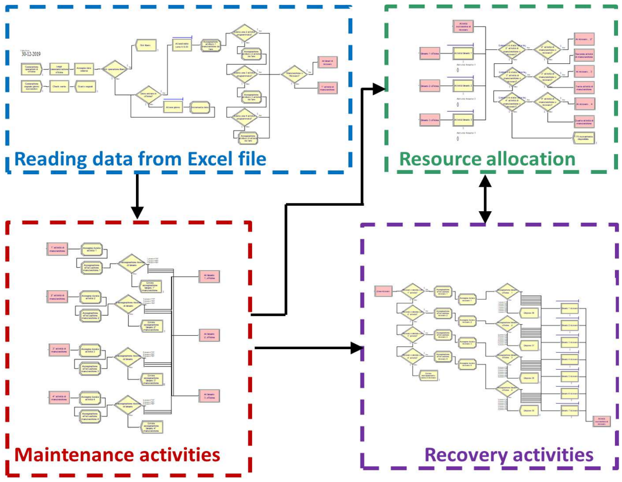

Fig. 5. Arena model modules

lines connecting the City of Turin with the surrounding belts. In particular, the case study analyzes a scheduled service between the rail stations of Rivarolo Canavese and Chieri, for a total length of 57 km per travel direction. The rolling stock operating on the line carries out maintenance work at the workshop of Rivarolo Canavese. This workshop is provided with two maintenance ways equipped with a pit and a bridge crane where all maintenance activities can be performed, and a third maintenance way that hosts trains that need the re-profiling of their wheels. A fleet of 20 convoys providing a service of 7 trains operating per day (of which 5 with double composition and 2 with single one for a total of 12 convoys per day travelling) has been simulated. The simulation campaign has been carried out for the entire year 2020. Moreover, four scheduled maintenance activities have been considered (i.e., R1, R2, R3 and wheels re-profiling, respectively lasting 1, 1 , 2 and 8 days).

Table I describes the scenarios tested using the above described simulation approach. The "worst case" refers to a situation where all the maintenance ways are occupied and the longest queues are present outside the workshop, while the "best case" represents the most favourable situation (i.e., minimum workload) for the workshop. Each scenario modifies the rolling stock turnaround time and the workshop calendar based on the duration of the events or the benefits brought by possible investments.

In order to compare the proposed scenarios, the following KPIs have been used:

- the actual processing times (expressed in hour);
- recovery times for lack of resources (expressed in hour);
- the Shift Coverage Ratio (SCR) defined as the ratio between the number of available convoys and the number of convoys needed for train compositions (if SCR > 1 the number of available convoys exceed what is necessary).

Furthermore, for scenarios n.1 to n.2f, the resilience (i.e., the system ability to re-establish the original maintenance scheduling after a disturbance) has been assessed, by calcu-

TABLE I

THE SCENARIOS TESTED

Type of scenario	*Scenario ID*	*Description*	*Timing*
Reference scenario	0	Scheduled rolling stock turnaround time	Deterministic maintenance times provided by the company
Unexpected event scenarios	1	Delay in workshop operations	Triangular distribution of processing times (a=0.9*m; m=deterministic value; b=1.5*m)
	2A	Fault on the operation side - worst case	Fault lasting 1 day
	2B	Fault on the maintenance side - worst case	Fault lasting 1 day
	2C	Fault - best case	Fault lasting 1 day
	2D	Fault on the operation side - worst case	Fault lasting 5 days
	2E	Fault on the maintenance side - worst case	Fault lasting 5 days
	2F	Fault - best case	Fault lasting 5 days
Investment scenarios	3	8 new wheels	Reduced times (due to wheels replacement instead of re-profiling).
	4	New maintenance way	Reduced times.

lating the difference between the moment when the failure event occur and the moment in which original maintenance planned schedule is re-established. In fact, after a failure, typically a rolling stock is replaced with another one compatible with those available in the parking area; this affects the working shifts scheduled for the following period.

Figure 6 shows, for each scenario, the distribution of total costs, subdivided between maintenance and waiting costs (i.e., related to the recovery area), expressed in hours.

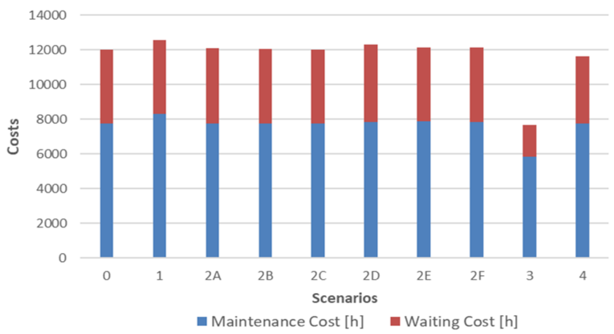

Fig. 6. Cost sharing for each scenario

Compared to the basic scenario (n.0), the most negative scenario is represented by scenario n.1, suggesting that the company should carefully focus on the minimization of the delays affecting the maintenance process.

Among the scenarios related to failures, the n.2d is apparently the most critical one, indicating how the Maintenance and Operation departments are strictly correlated. However, the increase in time is shared between the recovery area and the maintenance ways, making scenario n.2d less problematic than scenario n.2e in which the fault occurs on the worst day for maintenance. In fact, even if the overall increase is smaller for scenario n.2e, the single raise in the processing maintenance time is greater than scenario n.2d, causing a more critical situation due to the scarcity of resources. Furthermore, scenario n.2e is less resilient, with a recovery time equal to 18 weeks. This evaluation is carried out through a spreadsheet by reprogramming the shifts of the rolling stock following the disruptive event. This example demonstrates how discrete event simulation provides a clearer vision of where events affect the company processes, favouring an integrated planning between different parts of the company.

Among the proposed scenarios, the n.3 provides greatest benefits both on the operation and maintenance side. In support of this thesis, the evaluation of the SCR is presented in Figure 7.

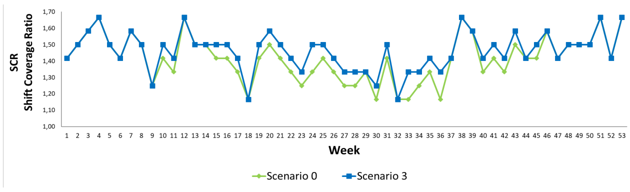

Fig. 7. Comparison between scenario n.0 and scenario n.3 - SCR index

Figure 7 shows that in the central part of the year (i.e., the period in which several wheels re-profiling are concentrated), the investment of new wheels - and the consequent reduction of working times in the workshop - brings great benefits on the operating side, with a SCR increase up to 16%. In addition, from the machine tour it is possible to estimate that each convoy occupies the workshop ways for 9 days per year, on average. Besides, the investment proposed in scenario n.3, generates a release of resources equal to 129 days, which is equivalent to the possibility of increasing the working potential of the workshop by 15 trains per year.

The simulation model also allows to evaluate the effects of the various scenarios for each individual resource. Figure 8 shows, for both scenario n.0 and n.3, the number of days of use for the three workshop ways. It can be noted that, due to its particular specialization, workshop way n.3 is consistently more used than the other two, representing a system bottleneck. The investment in new wheels, taken into account by scenario n.3, is therefore beneficial mainly for maintenance way n.3.

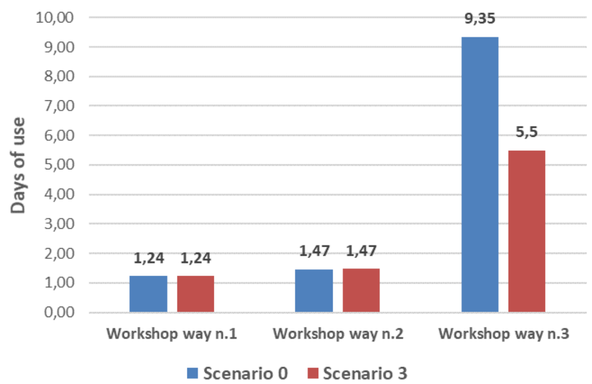

Fig. 8. Comparison between scenario n.0 and scenario n.3 - percentage use of maintenance ways

V. Conclusion

In this paper, a simulation approach devoted to support the planning of rolling stock maintenance and evaluate different maintenance strategies is proposed. In particular, the model allows to verify the goodness of maintenance plans in terms of compliance with all the constraints imposed both by the Operation and Maintenance side. The real datasets of an Italian rail local public transport company have been used to test the effectiveness of the proposed approach. The effects of unexpected events, as well as the benefits introduced by different investment policies, have been analysed, pointing out critical issues and system bottlenecks.

Finally, the presented simulation lays the foundations for the evolution of the railway maintenance sector towards a 2nd generation approach. Thanks to the available statistics of past events and the understanding of past interventions, effective variations in the maintenance cycle can be proposed. In particular, "on condition" maintenance can represent a scenario in the here proposed simulation campaign. Therefore, the proposed model can be included in the decision-making phase of the maintenance process, recommending the most effective policies to be adopted in the planning of the rolling stock turnaround time.

Future research will be devoted to apply the simulation model to other railway companies, considering different rolling stock used according to the service typology (passengers high speed and regional trains, or freight trains), and taking into account other types of layouts (with different maintenance specializations, number of workshops, etc.).

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