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Maintenance management of railway infrastructures based on reliability analysis

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ABSTRACT

Railway infrastructure maintenance plays a crucial role for rail transport. It aims at guaranteeing safety of operations and availability of railway tracks and related equipment for traffic regulation. Moreover, it is one major cost for rail transport operations. Thus, the increased competition in traffic market is asking for maintenance improvement, aiming at the reduction of maintenance expenditures while keeping the safety of operations. This issue is addressed by the methodology presented in the paper. The first step of the methodology consists of a family-based approach for the equipment reliability analysis; its purpose is the identification of families of railway items which can be given the same reliability targets. The second step builds the reliability model of the railway system for identifying the most critical items, given a required service level for the transportation system. The two methods have been implemented and tested in practical case studies, in the context of Rete Ferroviaria Italiana, the Italian public limited company for railway transportation.

1. Introduction

Railway infrastructure management plays an important role for answering the business pressure in rail transport. In fact, the societal expectations to safeguard people's safety and health on one hand and the market requirements for cost effectiveness and service level on the other are becoming more and more important in the novel competitive context coming from the liberalization of rail transports in Europe [1]. This situation creates a special challenging context for maintenance management, given the huge variety of technological items installed in a railway infrastructure, thus making the governance of resources involved in maintenance operations a very complex matter [2].

Indeed, many railway companies have to satisfy rules provided by safety regulations [3–5] that, in several countries, define maintenance procedures and even the frequencies for preventive maintenance with the primary goal of providing a high level of safety [6]. Besides, railway is competing with other forms of transport today, and railway companies are being split to provide transport services on one side and infrastructure services on another, to become more effective [7]. Furthermore, customers want more and more best quality service at lower cost, forcing the railway companies to optimize costs in every stage of the process, including maintenance.

To answer these issues, railway companies are producing significant efforts for the application of reliability based and risk-informed approaches to maintenance improvement, with the aim of reducing operational expenditure while maintaining high standards of safety. Also, they started to outsource some maintenance services for testing, by comparison, the correctness of their maintenance procedures [6,8].

In this context, Rete Ferroviaria Italiana (RFI), the Italian public limited company for railway transportation, started research efforts for improving its maintenance procedures by trying to better correlate the applied maintenance policies with the achieved reliability of the infrastructure. The collaborative work started with a literature analysis whose main results are herein reported.

Carretero et al. [6] addressed the problem of applying Reliability Centered Maintenance (RCM) to large scale railway infrastructures, in order to achieve an efficient and effective maintenance operation. Pedregal et al. [9] underlined how railway companies can restructure their maintenance management through the combined use of techniques, such as RCM and predictive maintenance, for achieving a rigorous control of service quality and costs effectiveness of trains' circulation. Kumar et al. [8] have shown how preventive railway maintenance works are performed to reduce the probability of a failure on the components of the railway infrastructure and/or to maximize the

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operational benefit. Chen et al. [10] evaluated railway power systems by Fault Tree Analysis (FTA) and investigated the impact of maintenance activities on overall reliability. Zio et al. [11] proposed a risk-informed approach for improving the service level of the railway network, while maintaining high standards of safety. Their approach makes use of importance measures to identify high-importance sections of the network, with the highest impact on the overall trains delay. Other scientific studies have foreseen a risk-informed optimization of railway tracks inspection and maintenance procedures [12], based on the application of ultrasonic inspections [13] and, in other cases, on intelligent condition monitoring [14] and fault diagnosis [5] of railway items.

Indeed, the existing models and research works for the railway industry demonstrate the importance of adopting a maintenance management based on reliability analysis. Nonetheless, the reliability analysis of equipment is not really included in a systemic evaluation, aimed at considering the effects on the whole transportation system. In particular, Ref. [11] has to be mentioned for its orientation toward a systemic evaluation for studying the effect of degradations in railway sections on the overall performance of the transportation system (i.e. overall trains delay). Today this is an important topic due to the market requirements of high service level together with cost effectiveness; more research works should be fostered to this concern.

In this respect, the data stored in the maintenance information system can be used to bring valuable information for identifying, driven by a reliability analysis, the actions to be taken in order to get improvements.

To this end, a reliability target achievable by the different items in the railway infrastructure should be established by the railway company: one important driver to this end is represented by the constraints imposed by safety issues, which require high levels for the reliability target. On the other hand, such a target should be fixed considering the criticality of each item for the trains' circulation, as well as the variety of technologies installed, thus requiring a reliability analysis both at equipment and system levels.

These issues – concerning the reliability analysis of the equipment and their effects for the transportation system – are not systematically addressed by literature regarding the railway sector; consequently it was clear that a specific modeling activity would have been needed for correctly answering the practical implementation needs of the RFI railway company. Thus a model was developed and verified in some application cases before implementation in the company's maintenance procedures.

The present paper describes the adopted modeling methodology for extracting knowledge from event data recorded into the Computer Maintenance Management System (CMMS). This knowledge is implemented in an analytical model for families of similar railway items as well as in the combination of the items of the railway system. The models can be used for assessing the current maintenance plans and taking decisions for new maintenance standards over the different varieties of railway items as well as for different railway tracks (i.e. for high or low traffic tracks).

A fundamental aspect of the proposed modeling approach is based on the relationship that is established between the railway system reliability and the transportation service level offered by the system itself. In fact this kind of information is of paramount importance for a railway company from a practical point of view. It may enable a more systemic evaluation of maintenance policies and plans, while at the same time verifying reliability targets fixed for component items and technologies by the railway company. Eventually, its close relationship with the application context may help an easy interpretation from the railway maintenance managers interested in evaluating innovative, reliability based, approaches to improve risk-informed decisions.

In order to describe the proposed methodology the paper is organized in this way: after the introduction, a description of the setting (i.e. the characteristics of railway items and tracks) is presented (in Section 2); the modeling methodology is then outlined (in Section 3), together with the potential areas of application (Section 4). Case studies in the RFI railway company context are eventually presented in Section 5.

2. Characteristics of a railway infrastructure

For understanding correctly the research assumptions and the adopted modeling methodology for reliability analysis a detailed description of the particular environment of the railway sector is needed.

A railway infrastructure has usually a wide geographic extension (referring to the case of Italy, about 16,000 km distributed all over the country) and it is composed of many and heterogeneous items (tracks, bridges, viaducts, tunnels, electrical transformation and conversion stations, electronic devices and stations for remote traffic regulation, etc.).

Tracks can be characterized in different ways. For example, they can be defined based on commercial criteria – number of trains flowing, passengers, railway line relevance, etc. or can be characterized by the type of service provided – run tracks (i.e. main tracks used for trains' circulation), centralized tracks (tracks used in stations for a train stoppage before its departure) and non-centralized tracks (truncated tracks).

Railway tracks belong to railway lines. Railway lines identify main transportation channels defined following commercial issues. Lines are spread all over the entire infrastructure and can be connected in some points (i.e. the railway hubs). A railway hub (a station or a coupling for example) can contain several lines that pass through or start/end there. An example of a railway hub is represented by a central hub sorting trains' traffic, connecting east and west or north and south of a country. Lines and hubs make up the entire infrastructure.

The railway infrastructure is characterized by the presence of a huge number of items, each of them playing different functions for trains' circulation: i.e. electro-mechanical and electronic devices (railway track circuits, automatic controls, etc.) and mechanical items (railway switches, sentry box, etc., see Fig. 1).

Furthermore in the railway sector, quite often the maintenance management complexity is increased by the fact that items have different technological properties (i.e. being manufactured in different times and by different producers, they are made of different components and based on different technologies); also it

Fig. 1. Railway tracks.

must be taken into account that they are subject to different operating conditions, according to their geo-location and usage (i.e. place where they are installed and trains' traffic along the specific line). All this complexity must be modeled accordingly, so to be able to handle in a quantitative way the system's reliability functions.

3. Modeling methodology

The adopted modeling methodology consists of two steps. The first step builds families of similar items, for which the same reliability target can be established as a standard level. Based on a system reliability analysis, the second step assesses how the failure of railway items impacts on the service level provided for the trains' circulation.

3.1. Building families of similar items

Building families has the objective to reduce the number of items to be considered into the railway infrastructure to a small set of items. The definition of a 'virtual item', representing a family of the original 'real' items, is used to this end. The rationale is to bring together, by a clustering procedure, a set of 'real' items that will establish a family, based on specific features they have in common. Indeed, features concern both technological properties and operating conditions of the items themselves, as depicted in Fig. 2.

Thus the clustering procedure is based on the two following methods:

- *Clustering by component's technology*—Items having a similar function are collected in 'technical classes', which are then subdivided in sub-classes according to features influencing their reliability. For example, the 'technical class' of railway switches is divided into 'sub-classes' such as electric switches (when these are electrically powered) or hand switches; the 'technical class' of track circuit is divided into the coded 'sub-class' (i.e. with codified currents) and the traditional one (Fig. 2).
- *Clustering by operating conditions*—'Volume of traffic' and 'type of track' are used as features to group items based on the similarity of the workload caused by trains' circulation. With specific reference to a railway station, items are also collected according to the 'type of rail', which is a further expression of the 'volume of traffic' in the station. For example, different 'technical classes' (e.g. railway switches, track circuits, etc.) are parts of railway lines featuring either high, medium or low 'volume of traffic'. Moreover they are part of lines where the 'type of track' is either a track dedicated to high-speed trains, electrified or non-electrified track. Eventually, in railway stations, the items may be also grouped based on the 'type of rails', i.e. 'run' versus 'non-run' (either centralized or truncated) tracks (Fig. 2).

In Fig. 3 the generation of the 'virtual item' data set is represented. Starting from the maintenance interventions on the 'real' items a, b, c, …, recorded in the CMMS, the time series of 'real' maintenance events is built (i.e., events are put in chronological order according to the time when they really happened, along a reference period). Then, these time series are put together, generating the time series (i.e. life data) of the 'virtual item', based on the length of the intervals between 'real' events (i.e. the time between maintenance and the time between failures). This mechanism provides a 'virtual' life data period of significant length appropriate for further analysis.

The industrial expertise of reliability engineers employed in the railway infrastructure maintenance allowed to obtain prior information on the 'real' events. In particular, according to prior information, maintenance procedures, either used for the repair after a failure or the preventive repair, have been assumed to enable rejuvenation, at each 'real' event, of the item to the condition 'As Good As New' (AGAN). This maintenance standard is motivated by the relevance of the items under study for their impacts on safety, and the primary goal of providing high level of safety on the infrastructure.

From a statistical point of view, the 'real' maintenance interventions on a given item are then considered as renewal events. As a consequence, when they are clustered into the 'virtual items', they are assumed as data sets independently sampled from density functions having identical probability and representing the behavior of an item to its first failure, starting from new.

This hypothesis needs to be verified since there are two approximations. The first approximation concerns the AGAN condition reached after the 'real' maintenance intervention. The second approximation is related to clustering 'real' events in a 'virtual' item: a risk is hidden in putting together events resulting from degradation processes of different 'real' items. To manage these approximations, we established a simple validation procedure to identify maintenance interventions that must be deleted

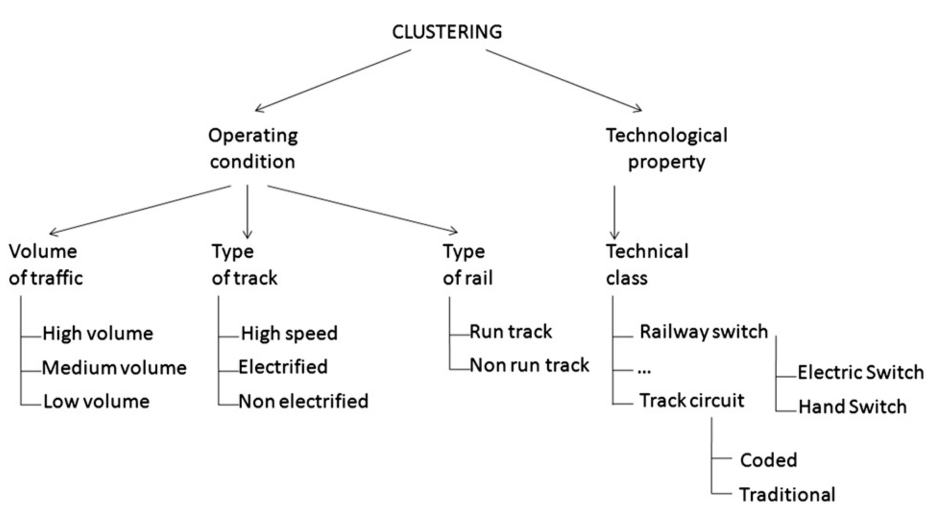

Fig. 2. Taxonomy of features of the railway infrastructure used as clustering drivers.

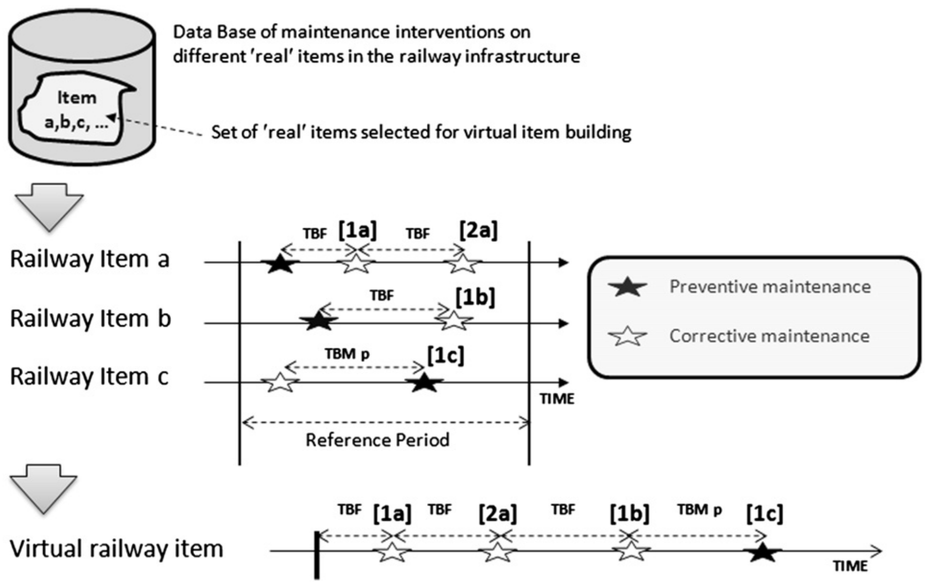

Fig. 3. Clustering of maintenance interventions for building the virtual railway item.

from the time series of a 'virtual item', because they represent outliers.[1]

The Weibull analysis (see e.g. [15,16] as traditional references), with multiple suspensions[2] (due to the preventive maintenance recorded in the 'virtual item' life data), can be applied after deleting the outliers. Its result is the Weibull probability density function, showing the best fit to the available data of a family of 'real' railway items.

It is worth observing that an organizational decision was made together with the RFI company for what concerns the analysis of the outliers: the outliers were processed apart, deciding to spend more time on each 'real' event in order to investigate the cause effectively motivating their state of being outliers. The reduced percentage share of the outliers (with respect to the total number of 'real' events in the sample) allowed such an intensive approach, based on man hours of technical personnel dedicated to the investigation. Moreover, it has permitted to consider the Weibull analysis, done after deleting the outliers, as a good approximation, being representative of the biggest part of the population of 'real' items and events.

3.2. Building the railway system model

The railway system model is built in order to evaluate how the transportation function (trains' transit and stop off) can be guaranteed by the infrastructure. To this regard, three generic states are considered:

- [State 2]. The railway system is working in a regular or nominal condition: train's transits and stop offs are done according to the transportation schedule (i.e., transportation capacity as planned).
- [State 1]. The railway system is working in a degraded condition while a maintenance intervention is done on a railway item; train's transits and stop offs are done but at a reduced transportation capacity, thus causing a reduced service level for the trains' circulation. In particular, this [state 1] occurs whenever transportation is possible only through one route because alternative routes are not available along the railway line; this may happen both when only one route is available between two stations of a railway line, or one route is available within a given station. More specifically, the single working route cannot support the entire traffic of the line in both directions and, as a lower bound of service level, it is assumed that only half transportation capacity is available, with respect to the total number of trains scheduled in all the directions; this assumption is proposed to model the inefficiency resulting from re-routing trains along the only working route.
- [State 0]. The railway system is not working due to a maintenance intervention; train's transits are not possible while the stop offs are, indeed, mandatory; therefore, no service provision for trains' circulation occurs at [state 0].

Based on these generic states as logical guidelines, a railway system model is then built to assess the impact of a failure of a railway item on the transportation capacity. The Reliability Block Diagram (RBD) modeling approach is adopted to this end: combining the series, parallel [17,18] and multi-state system (MSS) logics [19–21], the railway infrastructure is modeled, thus obtaining the overall system view wherein it is possible to assess the impact of failures of any single item. It is worth mentioning that the MSS logic is required because of the presence of degraded states (i.e. [state 1]), with degraded performance rates in terms of transportation capacity of the railway infrastructure. Indeed, the MSS logic has been already proposed for application to the railway industry, in order to study the effects of different speed restrictions (imposed by the degraded states of railway sections) on the overall performance of the transportation system [11].

[1] A simple procedure was defined in order to facilitate the validation of the statistical analysis based on the technical assessment of reliability engineers employed in the railway infrastructure maintenance. A first step of the procedure was aimed at the identification of the failure data comprised within the empirical distribution (shown by a failure histogram) and distant from the probability density function that could be drawn starting from the empirical distribution. These failure data could be defined as potential outliers, being representative of the items whose events could be considered as a sample of a different reliability law (i.e. items with lower or higher reliability). Therefore, the reliability engineers of the railway infrastructure maintenance should make technical verification on the potential outliers and decide if they should be deleted or not from the distribution.

[2] An information is defined as 'suspended' when the item's lifetime is known partially because it ended for reasons other than a failure (e.g. a preventive replacement is done).

Given the complexity of the railway infrastructure, the entire system is studied in terms of railway lines. The construction of a hierarchical model is needed to this end. At the upper level of the hierarchical model, a 'railway line' is the fraction of railway infrastructure that connects two stations identified as the source and destination of the transportation system (hubs of the infrastructure). From the reliability point of view, a 'railway line' is modeled as a series of subsystems such as 'railway tracks' and 'railway stations'. In case that different routes connect two hubs, the routes themselves are considered as subsystems composed of 'railway tracks' and 'railway stations', behaving in a MSS logic. Indeed, according to [state 1] of the transportation function, the MSS logic entails that the transportation capacity of the entire line is reduced to half capacity, whenever one route fails (i.e. one route is working out of two, because of a maintenance intervention on the other route).

As an example, Fig. 4 shows the RBD model of a railway infrastructure used by a train that must reach a station S2, departing from station S1 ('railway line' S1–S2). The train can follow two different routes.

- The first route includes 'railway track' TR2, 'railway station' S3 and 'railway track' TR3, instead the second route includes only 'railway track' TR4. These alternative routes are two subsystems in a MSS logic: the transportation capacity of the entire subsystem {TR2, S3, TR3, TR4} is then reduced to half capacity, after one route is not available because of a maintenance intervention.
- The subsystem of alternative routes is in series with other subsystems, i.e. other tracks and stations present along the line (i.e. hence, a series logic exists between TR1, TR5, TR6, S1, S2 and the subsystem {TR2, S3, TR3, TR4}).

Drilling down the hierarchical model, a 'railway track' (i.e. TR*x* in Fig. 4) is modeled as a composition of two component subsystems, i.e. the 'run tracks' (even and odd tracks). From the reliability point of view, a MSS logic exists among even and odd tracks: when a failure happens at a railway item installed in one of the tracks, the transit is allowed only through the still working track, at a reduced transportation capacity (i.e., according to definition of [state 1] of the transportation function, half transportation capacity is available from the working track, which is the only possible route).

A 'railway station' (S*x* in Fig. 4) is also modeled as two 'run tracks' (even and odd tracks), but in addition each of these is, by its turn, a subsystem enclosing the 'run track' itself and some 'centralized tracks', where the train can stop during the transit. From the reliability point of view, 'centralized tracks' are redundant parts, leading to a parallel reliability logic nested in the 'run track' subsystem of a station. Similarly to a 'railway track', an MSS logic exists among even and odd 'run track' subsystems of a station, performing at half transportation capacity (in accordance with [state 1] of the transportation function).

To complete the model at this level of the hierarchy, the 'tracks' are finally linked in a series logic with other component items, such as railway switches and track circuits, that, according to their function, serve to interconnect two adjacent 'tracks' along the railway line.

The following example (Fig. 5) can clear out the modeling mechanism at this level. First of all, let us model station S3 previously included in the railway line of Fig. 4.

- The station is modeled as a series logic of a subsystem of 'tracks' within the station (i.e., even and odd, centralized and run tracks) and entrance/exit electric switches (E./E. ES1 and E./E. ES2), as component items required to interconnect the subsystem of 'tracks' within the station with the adjacent 'tracks' connecting to other stations.
- Alternative routes are present within the station: if a train reaches the station, transit is allowed either through odd or even tracks. A MSS logic is then assumed within the station, whenever only one track is available (either even or odd) to support the entire traffic: accordingly with the assumption done for the transportation function at its degraded condition

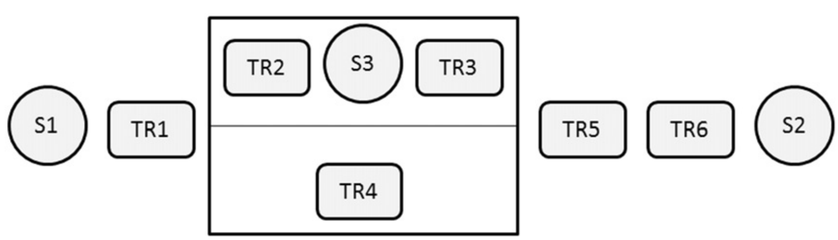

Fig. 4. Railway line connecting stations S1–S2.

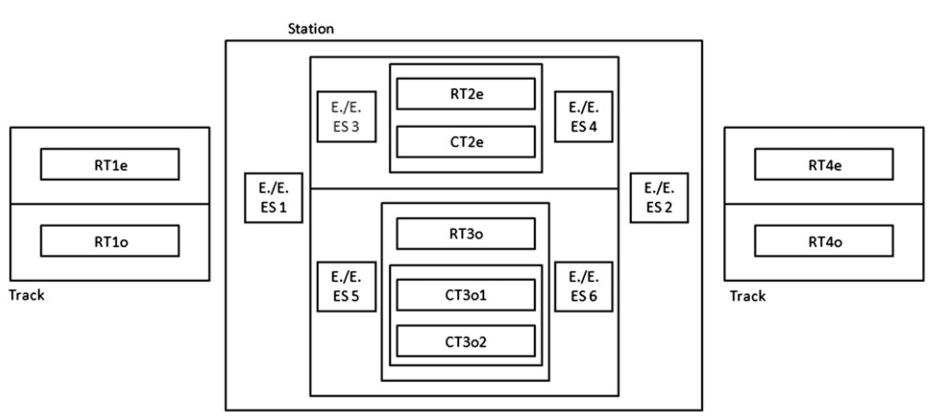

Fig. 5. From railway line to railway tracks.

(i.e. [state 1]), half transportation capacity is possible through either the even 'run track' {RT2e, CT2e} or the odd 'run track' subsystem {RT3o, CT3o1, CT3o2} of the station.

- It is worth observing that some component items should be required in order to enter an even or an odd 'run track' subsystem. In this example, two entrance/exit electric switches (E./E. ES3 and E./E. ES4) are needed to enter the even 'run track' subsystem {RT2e, CT2e}, so a series logic is defined between such entrance/exit component items and the 'run track'. The same logic is applied to the odd 'run track' subsystem {RT3o, CT3o1, CT3o2}, connected in series with its own entrance/exit electric switches (E./E. ES5 and E./E. ES6).
- The degraded condition (i.e. [state 1]) is only reached whenever parallel logics, present in the station, do not help avoiding it. In the example, the odd 'track' {RT3o, CT3o1, CT3o2} contains the 'run track' (RT3o) and two 'centralized tracks' (CT3o1, CT3o2): either the 'run track' or the subsystem of two 'centralized tracks' is needed for trains' transit and, within it, at least one 'centralized track' is enough; parallel logics are then nested in the odd track. The even 'track' {RT2e, CT2e} contains only one 'run track' and one 'centralized track' (RT2e, CT2e): the parallel logic herein nested is so limited to only one 'centralized track', beside the 'run track'. Similarly to other cases, it is worth observing that some component items should be required also at this level, to enter parallel 'centralized tracks' (e.g., to enter the branch of parallel centralized tracks CT3o1 and CT3o2). Fig. 5 omits, for simplicity, such component items.

Once a station is modeled, its adjacent 'tracks', connecting to other stations, can be modeled as well; for example let us consider TR2 and TR3, adjacent to station S3, in the railway line of Fig. 4, further modeled in Fig. 5.

- Even and odd 'run tracks' are present only in the adjacent 'tracks' (RT1e, RT1o in TR2 and RT4e, RT4o in TR3): this constrains re-routing possibility, since one alternative route can be used to re-route the traffic from/to other stations, whenever a failure happens along one 'track'. For this reason, even and odd 'run tracks' {RT1e, RT1o} are modeled according to an MSS logic, performing at half transportation capacity (considering the assumption for [state 1] of the transportation function). The same happens for even and odd 'run tracks' {RT4e, RT4o}.

The lowest modeling level ('railway item' level) finally encloses all the other component items placed inside each rail track (railway switches, track circuits, …, along a track). A series logic is used in order to represent the function of these component items; their failures may lead to unavailability of the track where they are placed and, as a further consequence, to a different transportation capacity, accordingly with the reliability logics expressed in the upper hierarchical levels of the railway system model.

For example, let us consider track circuits, placed in rail tracks connecting two stations (in previous Figs. 4 and 5, track TR2, composed of rail tracks RT1e and RT1o): different transportation capacities can result from the hierarchical model of the railway system, starting from different sets of failures for such component items.

- As a first set, let us consider just a failure occurring at a track circuit TC11e, in the rail track RT1e (Fig. 5). Accordingly with the series logic, the direct consequence is that rail track RT1e becomes not available; this causes a reduction to half transportation capacity, accordingly with the MSS logic expressed for the 'run tracks' {RT1e, RT1o} where TC11e is placed. At an higher level of the hierarchical model (Fig. 4), this leads to provide half transportation capacity through the route TR2–S3–TR3; this capacity has to be added to the half transportation capacity still available through route TR4.
- As a second set, let us consider failures occurring at track circuit TC11e, in the rail track RT1e, and at track circuit TC11o, in the rail track RT1o (Fig. 5). Accordingly with the series logic, the direct consequence is that both rail tracks RT1e and RT1o become not available; this leads to a no transportation capacity through the 'run tracks' {RT1e, RT1o} where the component items are placed. At a higher level of the hierarchical model (Fig. 4), this leads to provide just half transportation capacity available through route TR4.

The case of track circuits, placed in rail tracks within a station, can be elaborated in a similar way, except for the fact that the parallel logic, nested within the station, leads to different sets of failures, finally causing a degradation of the performance to either half or no transportation capacity through the station.

The approach for the railway system modeling is summarized in Fig. 6.

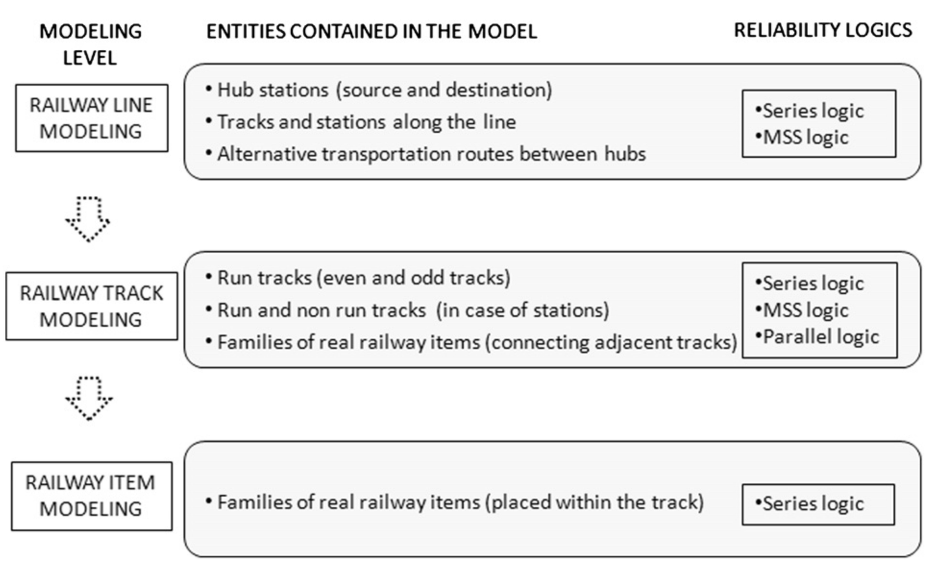

Fig. 6. Modeling of the railway infrastructure.

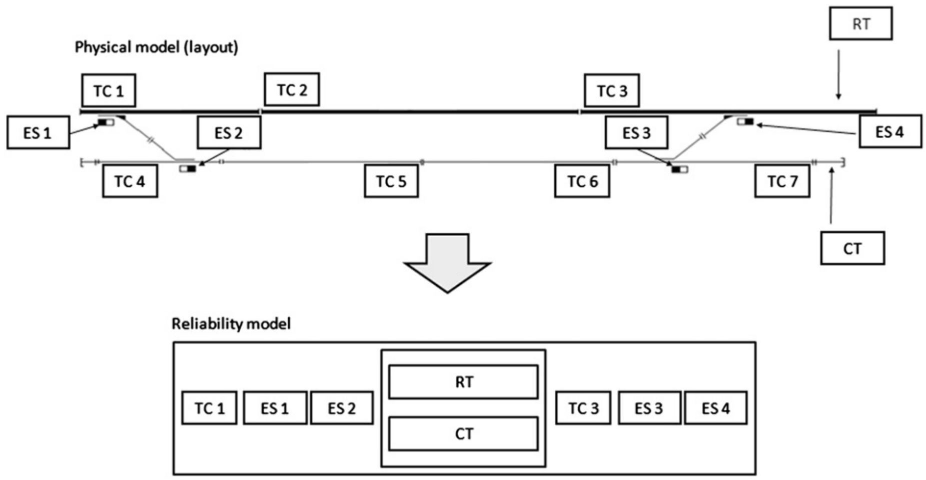

Fig. 7. Allocation of component items to a 'run track' subsystem.

It is worth pointing out that, in order to allocate component items to the railway track/line with a proper model of their functions with respect to the trains' circulation, physical layouts of the railway system may be required as input. Starting from this documentation, a railway system model is built by understanding the reliability logics as a result of interpretation of the trains flowing through the system.

A simple example is shown in Fig. 7 to clear out the concept. Fig. 7 shows the case of a 'run track' subsystem, made of the 'run track' itself and a 'centralized track'. The component items, needed for a train to enter/exit the subsystem, can be identified in the physical layout and then allocated as component items in a series logic with the 'run track' subsystem: these component items are track circuits TC1 and TC3 and electric switches ES1, ES2, ES3 and ES4 (see the figure). Other component items are allocated directly within each single track, accordingly to their function for trains' circulation through the track: component item TC2 should be nested in the 'run track' RT and component items TC4, TC5, TC6, TC7 should be nested in the 'centralized track' CT (Fig. 7 omits showing them in the reliability model, for simplicity).

Adopting the described framework, it is possible to represent the complete railway infrastructure and to conduct a reliability analysis such as for example to assess the impact of a single item/subsystem (e.g. a track circuit or a railway track) on the entire system (i.e. the railway line).

Indeed, following the system logics expressed in this section (synthesized in Fig. 6), a hierarchical model can be built by using a standard software tool for Reliability and Maintenance Engineering available on the market. RMES^{TM} tool [22] has been selected in our case because it was fitting properly with the railway system modeling requirements. In particular, RMES^{TM} supports two functions useful for building the railway system model: (i) a function for system reliability modeling at different hierarchical levels, enabling the construction of interconnected RBD models built, at different levels, as a decomposition of the whole system model (i.e. from upper to lower level sub-models); (ii) a function for Weibull analysis, enabling statistical data import and fitting for the component items placed at the lower level of the hierarchical model.

Thanks to these functions, once a railway line is identified as subject of analysis, a top down procedure is developed, thus reproducing – at each level of the railway system model – the reliability logics expressed by Fig. 6. It is worth reminding that the component items of the infrastructure are represented as 'virtual items', in accordance to the family clustering presented in Section 3.1. Hence, the component items, placed at the lower level of the hierarchical model built in RMES^{TM}, are the building blocks used to import data organized for making the Weibull analysis of the family clustering.

Once the railway system model is built and data imported for each family cluster, it is possible to analyze the reliability achieved at each level of the model, thanks to the reporting function supported by RMES^{TM}. In particular, both analytical and Monte Carlo simulation analyses are supported by RMES^{TM} and the out-coming results are shown in different reporting formats, calculated at different levels of a system reliability model. Thanks to these reporting features of the tool, it is then enabled the possibility to analyze the impact of items included in a railway infrastructure, considering either the track, station or line level for making the system reliability analysis.

As an example, after having built the correspondent model in RMES^{TM}, it is possible to analyze the impact of the reliability of track circuits on the reliability of either a track, a station, or a railway line including different tracks and stations, as in the case exemplified with Figs. 4 and 5. Moreover, if a reliability target is fixed by the railway company, e.g. on a given railway switch, two analyses can be done thanks to the system model built in RMES^{TM}: (i) the preventive maintenance interval on the railway switch can be identified to be compliant to the reliability target fixed by the company (e.g. 3 months can result from the Weibull model of the railway switch as the interval needed to obtain a reliability equal to the given reliability target 90%) and (ii) the reliability target achievable at a track, station or a railway line can be calculated as a consequence (i.e. this depends on the reliability logics expressed in the railway system model where the railway switch is placed).

3.3. Concluding remarks on the modeling methodology

The modeling methodology can be considered as a novel approach for maintenance management of railway infrastructure.

In particular, building families of similar items, with reliability targets established as standard levels, is not an innovative method by itself in reliability engineering. At this step of the methodology, the innovation stands primarily in the development of a reliability familiarization driven by railway operational features. In this concern, the taxonomy of technological properties and operating conditions of items, proposed to drive the familiarization (Fig. 2), can be considered as a novel tool for which this paper provides the first empirical proofs in the case of the

Italian railway infrastructure. Such empirical proofs may be helpful for future extensions to other railway infrastructures.

Another innovation stands for the system reliability analysis, at the second step of the methodology and, in particular, this is related to modeling the relationship between system reliability and transportation service level. The RBD modeling can be considered a novel tool to this end. More precisely, the adoption of RBD modeling approach, in order to assess how the failure of items impacts on the system level, is not a novelty; nonetheless, the hierarchical modeling of a railway infrastructure, to assess the service level provided for the trains' circulation, has never been proposed and, in the authors' opinion, this is an important gap to fulfill, in order to enable a more systemic evaluation of maintenance policies and plans. Also in this case, the hierarchical modeling approach, RBD model based, is achieving its first empirical proofs in the case of the Italian railway infrastructure, while future extensions may come out in the case of other railway systems. One extension is proposed in the concluding remarks, considering the work done by [11].

4. Implementation of the modeling methodology in practical cases

The proposed approach has been implemented in the Italian railway infrastructure management company.

4.1. Organization of railway transport system in Italy

Rete Ferroviaria Italiana (RFI) is a public limited company, part of Ferrovie dello Stato Group (FSGroup). Its mission concerns the Italian railway infrastructure management. In particular, after the liberalization of the railway transportation system in Italy, RFI became the railway infrastructure manager, whose responsibility is to guarantee the availability of the railway tracks and related equipment and to take care of traffic regulation. The unique shareholder of RFI is the Italian State and in particular the Ministry of Economy and Finance, that through service contracts gives to RFI the resources for maintaining the infrastructure.

The RFI railway company operates to:

- manage trains' circulation on the entire infrastructure with safety and quality standards;
- ensure efficient maintenance of the infrastructure;
- define and realize investments for new railway lines.

For what concerns rail transportation, market liberalization entailed that rail vehicles should be managed by Train Companies (TRCOs). TRCOs have a private management and are responsible for rail transportation. All TRCOs must have a license, issued by the ministry, and a safety certificate, issued by an independent organization. Following EU Directives for the safety and development of European railroads, the National Agency for Railway Safety ('Agenzia Nazionale per la Sicurezza delle Ferrovie') has been established. In this context, RFI's duty is to make available the National railway infrastructure to about ten TRCOs. These services are bought by TRCOs which pay a toll to RFI.

4.2. Needs to improve the maintenance management process

'The unfavorable economic conjuncture of the past years has caused a continuous contraction of Government resource availability, pushing to optimize maintenance costs without make a dent in reliability. Today, the objective of the company is to move to an asset management approach, thus increasing the infrastructure availability and improving the maintenance service by the implementation of a systemic viewpoint. This kind of improvement project was launched in the RFI railway company in the year 2000 with the introduction of a process oriented organization for maintenance management. The maintenance process is based on the implementation of the typical maintenance planning and control cycle (Fig. 8). For what concerns the upper level of the process, i.e. maintenance engineering, two important needs came up to the attention of management:

- the need to have maintenance plans customized for different clusters of railway items, that are subject to different operating conditions;
- the need to have certified maintenance standards in order to set up common maintenance rules to be shared among the different districts of the railway infrastructure.

These needs created favorable conditions for the implementation of the proposed methodology in the RFI railway company.

In particular, three types of assessment have been defined by RFI at the maintenance engineering level:

- *Family oriented policy assessment*—maintenance plans must be customized for different families of railway items (this issue can be supported by the family modeling methodology of Section 3.1);
- *Service oriented policy assessment*—maintenance plans must be verified, based on a required service level of transportation;

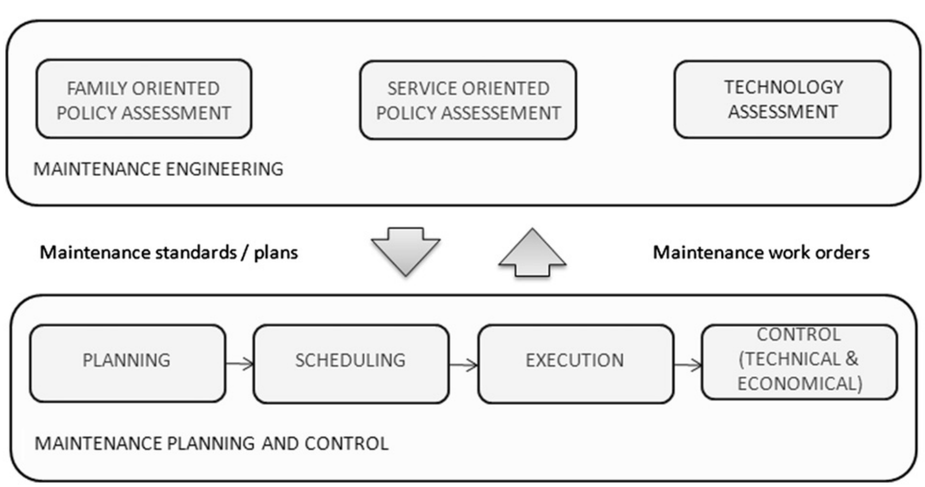

Fig. 8. General view of the maintenance management process of RFI railway company.

during the assessment, a particular concern must be given to the identification of critical items impacting on the system reliability (this issue can be supported by the railway system modeling methodology of Section 3.2);

- *Technology assessment*—a comparison of the reliability of different families of items, among different districts of the railway infrastructure, is required and, based on this comparison, reliability targets and maintenance standards should be established by a 'technical class' and its own 'subclasses' (this can be done by using families clustered by component's technology and by operating conditions as defined in Section 3.1).

5. Results of a preliminary study

The three types of assessment above mentioned have been validated in a preliminary study carried out together with the RFI railway company. The cases were identified in the scope of railway lines with 'high volume of traffic' and with 'electrified tracks'. Two main 'technical classes' were considered: railway switches and track circuits. In particular, the data sets, presented in Table 1, have been taken from the railway line Milano–Piacenza, a representative example of line with 'high volume of traffic' and with 'electrified tracks'. Moreover, each data set corresponds to the 'virtual item' data set, generated to represent a family of the original 'real' items, accordingly with the discussion of Section 3.1. It is worth observing that, in the Milano–Piacenza case, a total of 7 families has been created, including a total of 400 real items installed in the line.

The data sets have been collected from the maintenance interventions on the 'real' items recorded in SAP™ PM (plant maintenance) software system, already in use for the RFI railway infrastructure management. After deleting the outliers, failures and suspensions (due to preventive maintenance) have been used in order to form the time series (i.e. life data) of correspondent 'virtual items'. These time series were then input to RMES™ for making the Weibull analysis: this allowed identifying the best fit in terms of scale and shape factor of the Weibull function for each family in the Milano–Piacenza line. To this last concern, it is worth underlying that different data sets are available, in terms of total number of component items installed in the line, number of failures and suspensions: this is a matter to be considered for the quality of the enabled Weibull analysis and for the subsequent reliability analysis. Next sections provide more details on such analysis.

Table 1
'Virtual item' data sets (after deleting outliers).

Railway 'virtual' item	Total number of 'real' component items	Total number of failures on 'real' items	Total number of suspensions on 'real' items
Track circuit Traditional run track	12	36	26
Track circuit Coded run track	205	339	227
Track circuit Traditional centralized track	53	91	71
Rail switch Electric run track	71	252	0
Rail switch Other run track	7	50	16
Rail switch Electric centralized track	35	23	2
Rail switch Other centralized track	17	28	12

5.1. Family oriented policy assessment

The family oriented policy assessment has been validated in selected cases.

The example shown in (Fig. 9) is related to the analysis of track circuits, where the life cycle phase of each family has been identified in accordance to the bathtub curve theory[3] (Fig. 9, step 1). The current maintenance policy (AS-IS policy) has been assessed by verifying the reliability targets achievable with the currently running maintenance plans (Fig. 9, step 2, where the achievable targets are calculated based on the current preventive maintenance intervals). Then, a sensitivity analysis (TO-BE policy) was conducted by changing the maintenance preventive intervals and observing the reliability targets that could be achieved as a consequence (Fig. 9, step 3).

This way, it is possible to identify the right maintenance preventive intervals for each family, given the reliability targets to be achieved. It is important to underline how different families may achieve different reliability targets. For example, in the case of the traditional track circuit in the AS-IS situation (step 2 in Fig. 9), the reliability target is much lower in the 'run' (high traffic) than in the 'non-run' track (low traffic). The former needs more frequent prevention; therefore it is needed to reduce the length of the preventive maintenance interval, in order to increase the reliability target (see step 3 in fig. 9). For the latter, instead, it is possible to increase the preventive maintenance interval since, in the AS-IS situation, the achievable reliability target is rather high (as derived by lower traffic) and can be reduced. Doing so, it is possible to achieve a better balance of times and costs spent for the maintenance interventions for the different items of the railway infrastructure. Indeed, the better cost balance is subsequent to the possibility of deciding the maintenance plans that best fit the requirements coming from operations (i.e. different requirements from'run' and 'non-run' tracks).

Maintenance management of the RFI railway company found this approach helpful for studying possible changes of the current preventive maintenance intervals.

To this end, at the first step, the reliability target for each family should be defined by the maintenance manager, in compliance with given constraints regarding safety. In particular, the reliability target should be aligned with existent safety regulations, which depend on the railway item under concern and its function with respect to trains' circulation (e.g. a rail switch is in general important for safety issues). In this last concern, building families according to the taxonomy developed in this paper has been considered aligned also to the problem of compliance verification. For this reason, reliability targets, compliant with safety regulations, may be set up by proper procedures developed starting from such a taxonomy.

Secondly, the maintenance manager should define the preventive maintenance interval by considering the service level and cost effectiveness as additional criteria. At this step, the market requirements should be the leading driver: in particular, the service level may be also defined driven by the taxonomy, considering the higher market requirement for (higher) service level especially in the case of 'high volume of traffic', with 'high speed' and 'electrified tracks'; the reliability target should be defined accordingly with the (higher or lower) requirements for service level imposed by the market. At the end, the objective for cost effectiveness should be obtained through selecting the minimum cost of preventive maintenance interventions, subject to the verification of reliability targets.

[3] The life cycle phase of a family can be recognized by means of the shape factor of the Weibull probability density function. The shape factor was obtained after data fitting made by the RMES™ software.

STEP 1

FAMILY	LIFECYCLE PHASE
Track circuit traditional, run track	Useful life
Track circuit traditional, centralized track	Wear-out
Track circuit coded, run track	Infant mortality

STEP 2

FAMILY	AS-IS POLICY	R(T)
Track circuit traditional, run track	Preventive 6 months	86.9%
Track circuit traditional, centralized track	Preventive 6 months	94.6%
Track circuit coded, run track	Preventive 6 months	87.3%

STEP 3

DIFFERENT POLICIES FOR FAMILY Track Circuit traditional, run track	
POLICY	**R(T)**
Preventive maintenance 3 months (TO-BE POLICY)	93.3%
Preventive maintenance 6 months (AS-IS POLICY)	86.9%

Fig. 9. Example of family oriented policy assessment in the case of track circuits.

5.2. *Service oriented policy assessment*

The service oriented policy assessment supports the identification of critical items impacting on the system reliability. This is a top-down analysis, in the railway system model, i.e. starting from the upper level of railway line until finding the critical items at the level of component items, see Section 3.2 and Fig. 6.

Let us continue considering the railway line Milano–Piacenza. In order to allocate the component items to the tracks included in the line, a first activity consisted in making a list of all the real component items with their association to the tracks, accordingly with the codification already existent in SAP™ PM (Plant Maintenance) software system. A final analysis of physical layout, detailed for each station, was required to complete the allocation of railway switches to tracks, because of the insufficient information available from their SAP coding with respect to their function for trains' circulation.

On gathering such information, the railway system model of Milano–Piacenza line was built in RMES™, considering that each real 'item' should be replaced by the 'virtual item' modeled with its Weibull function, obtained from data sets shown in Table 1. At the end of this process, a model for service oriented policy assessment was then available to allow additional analysis with respect to those provided in Section 5.1.

This level of analysis may in fact show that even if two items belong to the same family (so they have a common behavior to failure), these may be more or less critical from a service point of view, depending on where they are placed and which function they play along the infrastructure. For example, if a railway switch is located right in front of the entrance/exit of a railway station, it will be much more relevant in comparison with others placed inside the station (critical railway switches in Fig. 10). This happens because if the one in entrance/exit goes down, the entire station and related traffic service go down too (i.e. series logic), while in the other case, the station can still be operative, at most with a reduced transportation capacity (according to the MSS logic).

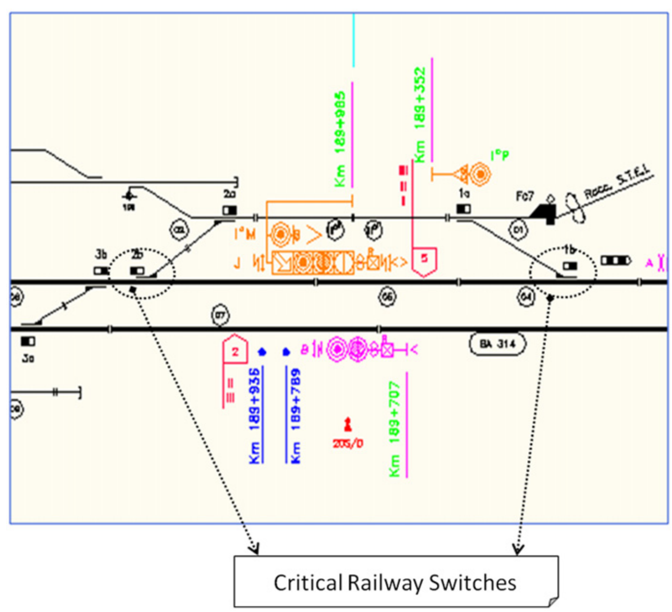

Fig. 10. Critical railway switches in a station.

In general, due to the modeling features of a railway system model (explained in Section 3.2), the reliability analysis, with respect to the transportation capacity as performance measure, can be used to divide items between more and less critical. In particular, the reliability logics, built in the railway system model, are used to develop a quantitative approach to help the RFI management identifying which component items mostly determine an effect on the overall system performance. The transportation capacity is used within this approach in order to define an influence factor for assessing how much the failure of a component item impacts on the service level provided for the trains' circulation. Hereafter, this parameter will be called 'Service Level Influencing Factor'.

More precisely, the 'Service Level Influencing Factor' has been defined as a performance measure to assess the reduction of the transportation capacity induced by a component item in a system reliability model, with respect to the as-planned transportation capacity. Indeed, a percentage 'factor' is used to show the relative reduction; for example, a 'Service Level Influencing Factor' equal to 25% means that the transportation capacity of the railway system model is reduced only by a quarter of the as-planned capacity.

The example of Figs. 4 and 5 can be reused in order to clear out the way the 'Service Level Influencing Factor' is assessed for each component item in the railway system model.

Let us consider, as a first example, the case of the electric switches at the entrance/exit of a station. These switches are required to interconnect the subsystem of 'tracks' within the station, with the adjacent 'tracks' connecting to other stations. These component items can have different impacts depending on the route, along a railway line, where the station is included.

- In the case of the electric switch at the entrance/exit of station S3 (E./E. ES1 and E./E. ES2 of Fig. 5), the 'Service Level Influencing Factor' is equal to 50%. The reduction of transportation capacity is total within the station (the switches being in a series logic with the subsystem of 'tracks' within the station, which results in a 'Service Level Influencing Factor' equal to 100%), but the station is part of one of two alternative routes in the 'Railway Line' S1–S2 (see Fig. 4): as a consequence, the reduction of trains' circulation occurs just in half of the routes (which means an MSS logic; hence from a 'Service Level Influencing Factor' equal to 100% within the station, we obtain a 'Service Level Influencing Factor' equal to $100\% \times 50\%$ within the line).
- In the case of the electric switches at the entrance/exit of station S1 or S2 (see the stations in Fig. 4), the 'Service Level Influencing Factor' gets worse and becomes equal to 100%. Indeed, S1 or S2 is just along the only existing route; no alternative route is available to sustain the traffic; the impact is then total (i.e. all is in a series logic which leads to a 'Service Level Influencing Factor' equal to 100% both within the station and for the line).

Let us now consider, as a second example, the electric switches of entrance/exit needed in order to allow the transit through the even or odd 'run track' subsystem in a station.

- In the case of entrance/exit electric switch of an even or odd 'run track' subsystem in station S3 (either E./E. ES3 and E./E. ES4 or E./E. ES5 and E./E. ES6 of Fig. 5), the 'Service Level Influencing Factor' is equal to 25%. Indeed, according to the MSS logic between the subsystems, the reduction of transportation capacity is partial within the station ('Service Level Influencing Factor' equal to 50%). The station being part of one of two alternative routes in the 'Railway Line' S1–S2, the reduction of trains' circulation occurs just in half of the routes (i.e. from a 'Service Level Influencing Factor' equal to 50% within the station we obtain a 'Service Level Influencing Factor' equal to $50\% \times 50\%$ within the line).
- In the case of entrance/exit electric switch of an even or odd 'run track' subsystem in station S1 or S2 (see the stations in Fig. 4), the 'Service Level Influencing Factor' is equal to 50%. As for station S3, according to the MSS logic between the subsystems, the reduction of transportation capacity is still partial within the station (i.e. 'Service Level Influencing Factor' equal to 50%). Since the station is part of one existing route in the 'Railway Line' S1–S2, the reduction of trains' circulation within the station completely affects the route (i.e. from a 'Service Level Influencing Factor' equal to 50% within the station we achieve a 'Service Level Influencing Factor' equal to $50\% \times 100\%$ within the line).

A similar method can be applied to other component items in the railway system model. In general terms, it can be stated that the reliability logic, built in the railway system model (see Fig. 6 for a summary), is driving the calculation of the 'Service Level Influencing Factor' through a bottom up procedure: firstly, a component item is assessed for its impact on the subsystem where it is directly included (either a station or a track). Henceforth, the assessment is further developed by going up modeling levels of the railway system model until the railway line level is reached; the assessments done at different levels are then combined to obtain the 'Service Level Influencing Factor' measuring the reduction of transportation capacity for a railway line between two stations as hubs. Therefore, by means of the calculation of the 'Service Level Influencing Factor' of each component item in a railway line, the service oriented policy assessment can help maintenance managers to set up maintenance interventions priorities. This eventually allows aligning the maintenance interventions plan with the requirements of the service level of a given transportation system.

Maintenance management of the RFI railway company found this concept helpful to add a perspective when studying possible changes of the current preventive maintenance intervals. Such a concept was acceptable for the standard thinking of reliability engineers employed in the railway infrastructure maintenance: indeed, the method resembles some existing methods for risk analysis used in RFI, combining the aspect of occurrence and severity of failures. In particular, personnel of the RFI company saw some potentials for the development of a new risk matrix where occurrence is calculated through the reliability model of different families of items while severity corresponds to the 'Service Level Influencing Factor' of each item in a given railway system model. Considering specifically the severity, it is important to underline how the 'Service Level Influencing Factor' was perceived by the RFI personnel as a novel measure in order to take into account the effect of a component item on the overall system performance.

As a followup of the general acceptance of the method, a new procedure for risk analysis has been envisioned. The first step of the analysis is based on the identification of either critical stations or tracks between stations along a line. Once these are identified, a more detailed analysis at a lower level – track level – has to be done to identify the critical items (i.e. this was the case of the station in Fig. 10). This two-stepped criticality analysis is possible thanks to (i) the Weibull analysis described in Section 5.1, and (ii) the railway system model herein developed and analyzed at different levels (i.e. station and track levels), thanks to the reporting functions of RMES™. Indeed, starting from these modeling features, a risk analysis can be deployed, considering in a unique view the reliability of different families of items and their 'Service Level Influencing Factors' for the railway line.

5.3. Technology assessment

The technology assessment brings in the identification of the reliability behavior of railway items according to different technologies. As an example, let us consider two different families of track circuits: a traditional track circuit and a coded one. These two families are sub-classes of the track circuit 'technical class' and are differentiated because of their technology.

Table 2
Technology assessment of families of track circuits.

Family	Policy	*R*(T) (%)
Track circuit Traditional run track	Preventive 3 months	93.2
Track circuit Coded run track	Preventive 3 months	92.5

The reliability analysis made on the two families of track circuits installed in run tracks (Table 2) shows that the traditional technology, less complex from a functional view point, is more reliable in comparison to the new more complex technology (coded track circuit), with the current preventive maintenance interval (of 3 months). Indeed, the technical personnel of the RFI railway company could motivate different reliabilities based on the different technologies of such component items, thus interpreting the results of the reliability analysis as aligned to the expectations according to their technical knowledge on the way the items may work (and fail).

Enlarging the analysis to items of the same 'technical class' and 'subclasses', working under different operating conditions (i.e., experienced in different rail districts), the reliability targets achievable by each technology may come out. This has big implications from a maintenance and service point of view. In fact, the technology assessment can bring the infrastructure manager to think on technologies to be adopted and when to activate interactions with the technology providers in order to ask redesign/improvements or at least to redefine maintenance standards.

Maintenance management of the RFI railway company found this concept helpful in order to widen the perspective to an asset management approach, by extension of decision making in the scope of the asset life cycle. This preliminary result may be in fact interesting to activate further analysis in an enlarged scope, e.g. by involving directly the technology providers to analyze the reliability behavior of component items under operating conditions experienced in different rail districts.

6. Concluding remarks

This paper introduces a modeling methodology aimed at supporting maintenance management of railway infrastructures based on reliability analysis. A specific objective of the work is to provide the capability to assess the current maintenance standards/plans of a railway infrastructure and, when needed, to propose or initiate improvement actions driven by a reliability analysis of the railway items, by taking into due account the effects on the transportation service level. By the tests taken from the case studies carried out together with the Italian RFI railway company, it was possible to verify how the reliability analysis enables rethinking maintenance plans/standards. Also the proposed reliability analysis can be used to evaluate a differentiation of the maintenance plans/standards in view of cost reduction, without making a dent in the reliability of the infrastructure.

The modeling methodology can be considered for extension to other railway infrastructures, in order to achieve a general validation beyond the RFI case. Indeed, its close relationship with the application domain may help sharing the methodology in other railway contexts. In particular, the authors believe that the interested readers may find the following issues relevant for further developments in their own context:

- the taxonomy of features of railway infrastructures can be considered helpful to drive the familiarization of component items for the purpose of reliability analysis and for further integration of criteria for the definition of reliability targets (e.g. definition of reliability targets subject to safety levels);
- a set of application-dependent rules can be easily derived from the hierarchical RBD modeling approach herein proposed for railway system modeling; this can be a starting point for system reliability modeling of railway infrastructures;
- the initial proof of the different areas of application in maintenance management shown in the paper (family oriented policy assessment, service oriented policy assessment and/or technology assessment, as defined in RFI context) may provide ideas for the integration of existent maintenance management processes.

Further advances of the modeling methodology can be envisioned as well. These can be obtained by the integration of methods for Condition Based Maintenance. In this regard, the adoption of the Proportional Hazard Reliability Model [15] can be studied as a promising tool to allow decisions based on the risk of operations measured by the age and conditions of an equipment. Such a kind of solution could enable a balanced control of maintenance costs while preserving the required safety and service levels.

Another advance can be envisioned considering the further development of the hierarchical RBD modeling of a railway infrastructure, proposed in our work in order to assess the service level provided for the trains' circulation. Indeed, some gaps have to be fulfilled in the present modeling approach, such as the capability to represent speed restrictions through degraded railway sections. In this respect, [11] can be considered as a complementary proposal to our work, and can be used as a source of inspiration to integrate such an important modeling feature.

Last but not the least, due to the complexity of a railway network, the development of a set of importance measures, in order to identify high-importance equipment with respect to their impacts on the overall performance of the transportation system, can be another relevant research direction. Our proposal has been focused on a 'Service Level Influencing Factor' measuring the reduction of the transportation capacity with respect to the as-planned capacity. A further integration of other importance measures can be foreseen: the work [11] is a reference also to this end and can be taken into account for developing importance measures related to train delays, resulting from traffic congestion. Such measures may find, in our expectations, potentials for application in the assessment of the effects on the overall performance of the transportation system, not only considering maintenance planning decisions, but also the scheduling of condition based maintenance actions.

References

[1] UNIFE—The European rail industry. Annual report 2009. 〈http://www.unife.org/uploads/UNIFE_Annual_Report_2009.pdf〉 [accessed February 2010].
[2] UNIFE—The European rail industry. Annual report 2008. 〈http://www.unife.org/uploads/UNIFE_AR2008.pdf〉 [accessed January 2009].
[3] Den Hertog D, Van Zante-de Fokkert JI, Sjamaar SA, Beusmans R. Safe track maintenance for the Dutch railways, part I: optimal working zone division. Technical report. The Netherlands: Tilburg University; 2001.
[4] Van Zante-de Fokkert JI, Den Hertog D, Van den Berg FJ, Verhoeven JHM. Safe track maintenance for the Dutch railways, part II: maintenance schedule. Technical report. The Netherlands: Tilburg University; 2001.
[5] Roberts C, Dassanayake HPB, Lehrasadb N, Goodman CJ. Distributed quantitative and qualitative fault diagnosis: railway junction case study. Control Engineering Practice 2002;10:419–29.
[6] Carretero J, Pérez JM, Garcìa-Carballeira F, Calderòn A, Fernàndez J, Garcìa JD, et al. Applying RCM in large scale systems: a case study with railway networks. Reliability Engineering & System Safety 2003;82(3): 257–73.

[7] Vatn J, Aven T. An approach to maintenance optimization where safety issues are important. Reliability Engineering & System Safety 2010;95:58–63.
[8] Kumar UD, Crocker J, Knezevic J, El-Haram M. Reliability, maintenance and logistic support—a life cycle approach. Boston/Dordrecht/London: Kluwer Academic Publishers; 2000.
[9] Pedregal DJ, Garcıa FP, Schmid F. RCM2 predictive maintenance of railway systems based on unobserved components models. Reliability Engineering & System Safety 2004;83:103–10.
[10] Chen SK, Ho TK, Mao BH. Reliability evaluations of railway power supplies by fault-tree analysis. IET Electric Power Applications 2007;1(2):161–72.
[11] Zio E, Marella M, Podofillini L. Importance measures-based prioritization for improving the performance of multi-state systems: application to the railway industry. Reliability Engineering & System Safety 2007;92:1303–14.
[12] Podofillini L, Zio E, Vatn J. Risk-informed optimisation of railway tracks inspection and maintenance procedures. Reliability Engineering & System Safety 2006;91:20–35.
[13] Vatn J, Svee H. A risk based approach to determine ultrasonic inspection frequencies in railway applications. In: Proceedings of the 22nd European safety, reliability & data association seminar; 2002.
[14] Gutsche K. Intelligent, cost efficient maintenance of railway switches based on condition data. In: Proceedings of 22nd international congress on condition monitoring and diagnostics; 2009.
[15] Jardine AKS, Tsang AHC. Maintenance, replacement and reliability: theory and applications. Boca Raton: CRC Press; 2006.
[16] Murthy DNP, Xie M, Jiang R. Weibull models. New York: Wiley; 2004.
[17] Birolini A. Reliability engineering: theory and practice. Berlin: Springer-Verlag; 2004.
[18] Ramakumar R. Engineering reliability: fundamentals and applications. Englewood Cliffs: Prenctice-Hall; 1993.
[19] Levitin G. Block diagram method for analyzing multi-state systems with uncovered failures. Reliability Engineering & System Safety 2007;92:727–34.
[20] Lisnianski A, Levitin G. Multi-state system reliability. assessment, optimization and applications. Singapore: World Scientific; 2003.
[21] Lisnianski A. Extended block diagram method for a multi-state system reliability assessment. Reliability Engineering & System Safety 2007;92:1601–7.
[22] R-MES CGS Company. Reliability and maintenance engineering system. ⟨http://www.mes.cl⟩ [accessed July 2011].