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Non-destructive Technologies for a Sustainable Assessment and Monitoring of Railway Infrastructures: a Focus on GPR and InSAR Methods

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Health monitoring of ballast in railway infrastructures is crucial to assure long-term structural stability. To this extent, an efficient and sustainable management of maintenance operations is fundamental for asset owners in setting up strategic and effective action plans. Amongst the available methods to assess the conditions of railway infrastructures, non-destructive technologies (NDT) are gaining popularity due to their capability to overcome main drawbacks from conventional routine methods, such as digging trenches and visually inspecting sections along the track, assumed as critical.

The present study reports an overview on the use of the Ground Penetrating Radar (GPR) and the Interferometric Synthetic Aperture (InSAR) technologies for a sustainable monitoring of railway infrastructures. Specifically, main conventional and non-destructive methods utilisedd for maintenance of railway ballast materials are presented, with a special focus on their sustainability. A review about research methods on the use of GPR and InSAR technologies for railway infrastructure monitoring is also reported, including main investigations carried out in the laboratory and the real-life environments. Furthermore, a conceptual framework based on an integrated approach including satellite-based and ground-based investigations is proposed, where network and local level information can be merged for a more effective detection of critical sections and the implementation of an advanced predictive maintenance system.

Keywords: Railway Infrastructures; Sustainable Assessment and Monitoring; Non-Destructive Testing; Ground Penetrating Radar (GPR); Interferometric Synthetic Aperture Radar (InSAR); Advanced Predictive Maintenance System

1. Introduction

Modern transportation greatly relies on ballasted railways, as they have proven to offer good drainage and bearing performance capabilities at relatively moderate costs, as opposed to other railway construction types. Indeed, a major role of these infrastructures is to sustain the journey of both commuters and economic goods on a daily basis between major cities and economic transport spots [1].

From top to bottom, a ballasted railway track is composed by the steel rails, anchored to the sleepers through a fastening system, a coarse ballast layer often laid over a finer graded subballast layer and, lastly, the subgrade [2]. According to literature, this system is usually classified as to be divided into two major components, namely, a superstructure and a substructure. However, this classification can vary based on literature sources [3]. [4], [5], [6], as the ballasted layers can be either included as part of the superstructure [7] or the substructure [8].

For the purpose of this paper, the authors have assumed the track configuration shown in Figure 1, with the substructure being formed by the subgrade and the ballasted layers, and the superstructure including the sleepers, the fastening mechanism and the steel rails [2]. All these components act as parts of a more complex system reacting to the effects of loads exerted by the passing convoys and assuring proper safety and efficiency conditions of the transport.

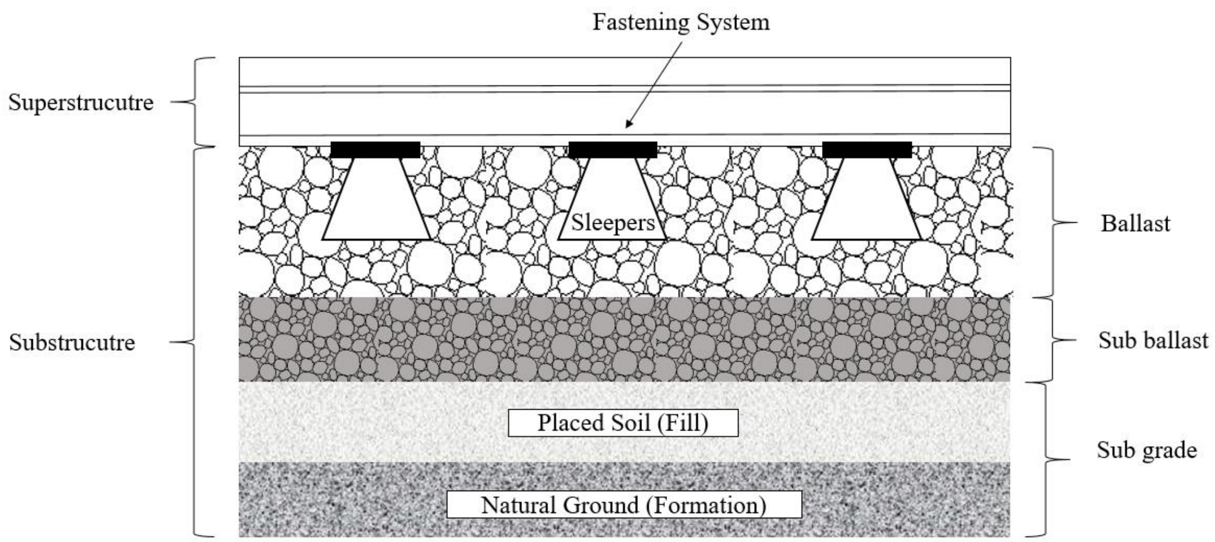

Figure 1 – Cross-section layout for a ballasted railway

It is clear that these functions are effectively fulfilled only whether the full structure is maintained in proper conditions during its service life [9]. This is particularly true for ballast layers, due to their fundamental structural functions, such as i) bearing the compression stresses applied to the sleepers; ii) preserving the alignment of the rails; iii) rapidly draining water and other liquids out of the track [10, 11]. To that extent, the monitoring of ballast conditions with an appropriate time frequency is crucial to ensure that the above functions are not inhibited by the degradation of the material.

The durability of ballast is severely affected by the abrasion of sharp edges of aggregates and their fragmentation into finer material under the effects of repeated loading cycles. This topic has been widely addressed in the literature, typically applying the Los Angeles Abrasion (LAA) test on ballast samples in order to relate a variation in the aggregate shape characteristics to the abrasion index obtained by LAA standards [12, 13, 14, 15, 16]. Indeed, repeated stress cycles generated by railway traffic can rapidly damage the ballasted layer and, in turn, they can further cause formation of fouling materials (particles ≤ 1.2 cm) [17], with a negative impact on the whole track stability.

In general, this contamination process starts as the voids between the aggregates get filled with fine materials [18]. Amongst the various different causes for the formation of ballast fouling, the most common are the fragmentation of the aggregates (76%), the migration of fine-grained material from the subgrade (13%), the infiltration of sub-ballast materials (7%), the wearing of concrete or wooden sleepers (3%) and the infiltration of weathered particles and coal droplets (1%) [19, 20]. Regardless of the source, fouling can inhibit the strength and drainage capacity of the ballast layer [11, 20] and, hence, it can severely affect safety conditions of the track. As an example, in case of existing poor drainage conditions caused by a reduction of the intergranular voids, water accumulation in the ballast layer may determine a considerable drop in the stiffness of the material [21]. Accordingly, an inaccurate estimation of fouling may affect the planning of effective maintenance strategies, and eventually lead to peripheral and less effective decisions. As an example, introducing traffic control signals (e.g., the provision of temporal/permanent speed limits) in case of cumulated deformations on the rails may contribute to increase the likelihood of catastrophic events, such as train derailments [9]. Therefore, a rapid and effective diagnosis of fouling and moisture levels within the ballast layer is crucial for asset owners in setting up effective maintenance programmes [22].

Health assessment of ballast is conventionally performed by visually checking the condition of the superstructure at given locations along the track using inspection trenches. However, these methods are clearly destructive, labour-intensive and time-demanding, and they can provide significant information only at the location of the inspected section. On the opposite, non-destructive testing (NDT) methods are being increasingly adopted due to their capability to overcome the main disadvantages of conventional methods. Amongst the various NDT methods available on the market, the Ground Penetrating Radar (GPR) technology is gaining popularity with the assessment of ballast, as it permits the acquisition of dense and accurate information through efficient and sustainable surveys. According to its non-destructive nature and the high productivity, GPR allows avoiding important earth movements and limit the consumption of non-renewable resources. Parallel to this, the Interferometric Synthetic Aperture Radar (InSAR) is nowadays emerging for the monitoring of ballasted railway tracks at the network level, as it allows to collect data on wide portions of territory across different time intervals.

Within this framework, the present work reports an overview on the use of the GPR and the InSAR methods for a sustainable monitoring of railway infrastructures. To elaborate, Section 2 shows the decay modes of ballast highlighting main characteristics and effects of the mechanisms leading to ballast deterioration. The main conventional and non-destructive methods for railway ballast maintenance are discussed in Section 3, with a special focus on sustainable maintenance activities. Section 4 reports a review of research methods and applications on the use of InSAR and GPR techniques in railway infrastructures at the laboratory-scale of investigation as well as in real-life practice. The benefits of a newly-proposed network-level NDT monitoring approach are then discussed and conceptualised in Section 5. Conclusions and main remarks are reported in Section 6.

2. Railway ballast decays: overview and assessment methods

Different types of decay may occur on a ballasted railway, as the substructure and the superstructure can deteriorate in different modes. In particular, structural deformations generates in the substructure and are typically related to issues such as polishing of ballast, poor drainage and formation of ballast pockets [23, 24]. In addition, various failures observed at the superstructure level may instead originate from decay evolving in the substructure. As an example, a track substructure with poor structural properties may reflect on the loss of the rail regularity leading to significant wearing or even to failure of rails, sleepers and fasteners [25].

Major superstructure track failures can be broadly grouped as i) faults linked with the superstructure geometry (e.g., alignment, longitudinal levellingand gauge) and ii) faults linked with the rail surface (e.g., surface, corrugation) [26]. It is worth noting that the above classes of failures are strictly dependent. Although rail surface quality does not directly affect the safety and comfort aspects of passengers, it can affect the quality of the alignment and, consequently, the infrastructure lifetime [27].

Under a structural point of view, the strength characteristics of the substructure components are affected by excessive fouling in terms of a reduced durability, the formation of mud-holes, reduced permeability (drainage) and stability features and an increase of permanent deformations [28, 29].

With reference to the ballast fragmentation, fouling is caused by the formation of smaller crushed aggregates [30] with a gravel-like consistency. At an early stage, this occurrence can erroneously linked with an increase in the strength of the ballast layer, due to the high-strength fragments in the voids limiting the settlement of larger ballast aggregates. However, this fictitious increase of the ballast mechanical properties reflects on a reduction of both the resilience of the track and the permeability of the layer. Indeed, a thin threshold divides inducedstrength conditions of ballast layers from their fragmentation and constraints on their drainage capacity, as reported in the literature [31-33].

2.1 Fouling quantification

Fouling affecting a ballasted track can be qualitatively classified in three main classes, i.e., clean, moderately fouled and highly fouled ballast [34] (*Figure 2*).

Clean ballast basically represents the as-built conditions of new ballast aggregates with proper air-void contents. As the amount of pollution increases due to the degradation mechanisms, the high-fouling level is reached once all the air voids gets filled with fine particles [35].

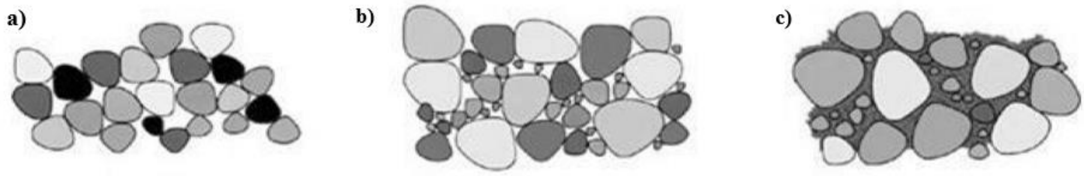

Figure 2 – Layouts of fouled ballast levels: a) clean ballast b) moderately fouled ballast c) highly fouled ballast

In quantitative terms, several indexes are reported in the literature to describe the various different fouling pollution levels in ballast layers. These indexes typically define the rate of fouling in terms of the size of the fine-grained particles filling the intergranular voids between the coarse-grained ballast aggregates [17, 36]. A description of the main fouling indexes is reported below.

<u>Fouling Index.</u> The Fouling Index (FI) (Equation (1)) proposed by [19] is commonly used in railway engineering practice and it has been extensively adopted in the US.

$$\boldsymbol{FI = P_{\%}^{4} + P_{\%}^{200}} \tag{1}$$

Where $P_{\%}^{4}$ is the percentage by mass of ballast passing the 4.75 mm (No. 4) sieve, and $P_{\%}^{200}$ is the percentage by mass passing the 0.075 mm (No. 200) sieve. *Table 1* reports different ballast fouling levels corresponding to the various proposed FI values [19].

Table 1 - *Categories of fouling according to [19]*

Fouling Level	**Abbreviation**	**Fouling Index**
Clean	C	<1
Moderately Clean	MC	1-10
Moderately Fouled	MF	10-20
Fouled	F	20-40
Highly Fouled	HF	>40

Volumetric Fouling Index. Fouling causes a variation of the original specific gravity of the ballast layer, as the original void ratio varies with an increase of the pollution from fines. As such, the number of contact points between fouled particles and ballast aggregates are proportional to the void volumes clogged up. Based on this, a Volumetric Fouling Index (VFI) (Equation (2)) was established by Ebrahimi et al. [17] to eestimate the volumes of contaminants in ballast subject to different fouling agents.

$$\boldsymbol{VFI = FI} \times \frac{\boldsymbol{G_s^r}}{\boldsymbol{G_s^f}} \tag{2}$$

with FI being the Fouling Index expressed by [19], G_s^r the specific gravity of the reference ballast material (~ 2.6), and G_s^f the specific gravity value of the considered fouling agent, respectively. This expression matches with that proposed by [37], evaluating the fraction of the total void volume of contaminated ballast through a percentage void contamination model (PVC). In addition, a similar volumetric model named Void Contamination Index (VCI) was developed by [38] to comprehensively estimate the volume of multiple fouling agents (e.g., clay and coal) relative to the total volume of ballast voids.

Ballast particle contact-point contamination. As mentioned, fines between coarser aggregates decreases the number of contact points between the ballast aggregates and, accordingly, it can affect the stiffness of the track [17, 28, 39, 40]. This model has been developed to determine the ratio of macro voids in the ballast matrices under various conditions of fouling by comparing the ballast conditions under investigation to reference clean ballast conditions [17] as follows:

$$\boldsymbol{e_{mac}^B} = (\frac{\boldsymbol{G_s^r \gamma_w V}}{\boldsymbol{M_b}} - \mathbf{1}) \tag{3}$$

where e_{mac}^B is the ratio of macro voids in ballast, G_s^r is the specific gravity of ballast, γ_w is the density of water, V is the total volume of the sample ballast, and Mb is the mass of ballast particles (> 12 mm) in the volume.

Breakage Index. The Breakage Index (BI) (Equation (4)) is calculated through the fractal gradation curve test [41], and it is expressed as the difference in the areas between the original and the final gradation curves . The index is expressed as follows:

$$\boldsymbol{B_{bal}} = (\frac{\boldsymbol{A}}{\boldsymbol{A+C}}) \times \mathbf{100} \tag{4}$$

with B_{bal} being the breakage index and A e C the gradation areas calculated through the gradation chart in *Figure 3* [42].

Relative Breakage Index. The Relative Breakage Index (RBI) (Equation (5)) is defined as the difference in terms of areas between the original gradation and the final gradation curves [42]. The index is expressed as follows:

$$\boldsymbol{B^{r}_{bal}} = \left(\frac{\boldsymbol{A}}{\boldsymbol{A+C+D}}\right) \times \mathbf{100} \quad (5)$$

where B^{r}_{bal} is the relative breakage index, and A, C, D are the gradation areas calculated through the gradation chart in *Figure 3* [42], [43].

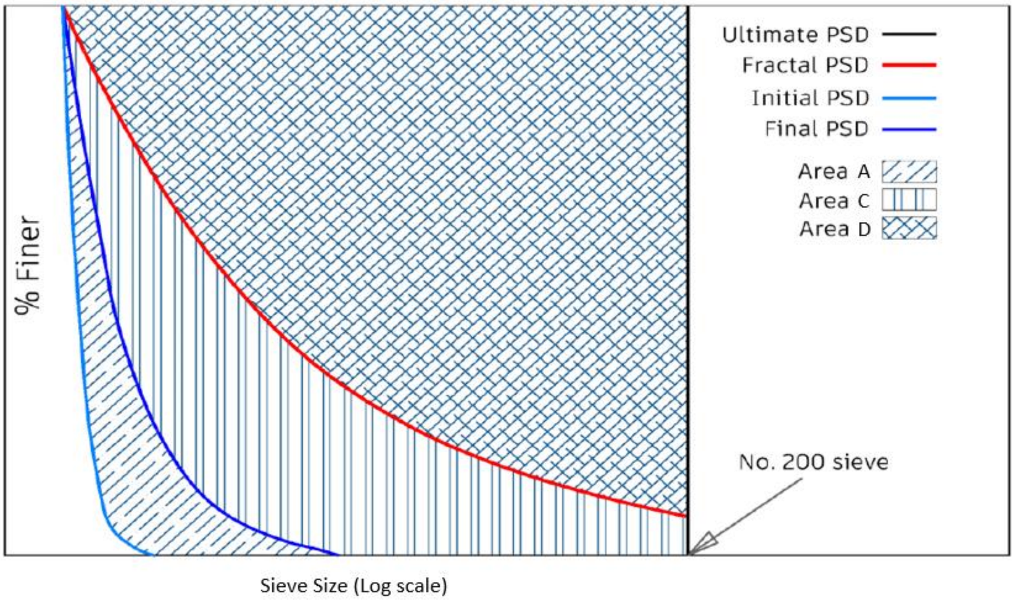

Figure 3 – Criteria for calculation of B_{bal} e B^{r}_{bal} [42]

Table 2 lists the main ballast degradation indexes and relevant literature in this area of research.

Table 2 – Ballast degradation index

Index	Abbreviation	Formula	References
Fouling Index (1)	FI	$\mathrm{FI} = \mathrm{P}^{4}_{\%} + \mathrm{P}^{200}_{\%}$	[19], [32]
Volumetric Fouling Index (2)	VFI	$\mathrm{VFI} = \mathrm{FI} \times \frac{\mathrm{G}^{r}_{s}}{\mathrm{G}^{f}_{s}}$	[17], [38]

Ballast particle contact-point contamination (3)	-	$e^{B}_{mac} = (\frac{G^{r}_{s}\gamma_{w}V}{M_{b}} - 1)$	[17]
Breakage Index (4)	BI	$B_{bal} = (\frac{A}{A+C}) \times 100$	[42], [41], [44]
Relative Breakage Index (5)	RBI	$B^{r}_{bal} = (\frac{A}{A+C+D}) \times 100$	[42], [44]

3. Railway ballast maintenance

3.1. Diagnosis and maintenance

A regular inspection of the railway network is fundamental to ensure the safety and efficiency of the asset by an early detection of critical sections and potential damage in the track. However, the maintenance of this complex system is a demanding task in terms of both costs and duration of the activities.

Within this framework, an effective assessment of the ballast layer and the subgrade conditions is crucial to plan timely interventions. This can contribute to reduce costs and to limit the impact on the safety of the infrastructure.

It has been observed that in case of limited funds available for the management of railway assets, the budget for maintenance (e.g., ballast cleaning and renewal operations) tends to be reduced accordingly. This approach is reasonable only for short-term interventions, as it is likely to jeopardise the long-term costs of the overall track asset. Indeed, a delayed planning of routine and extraordinary maintenance could escalate into more severe consequences and, thereby, it can lead to a dramatic increase of the costs for rehabilitation [9].

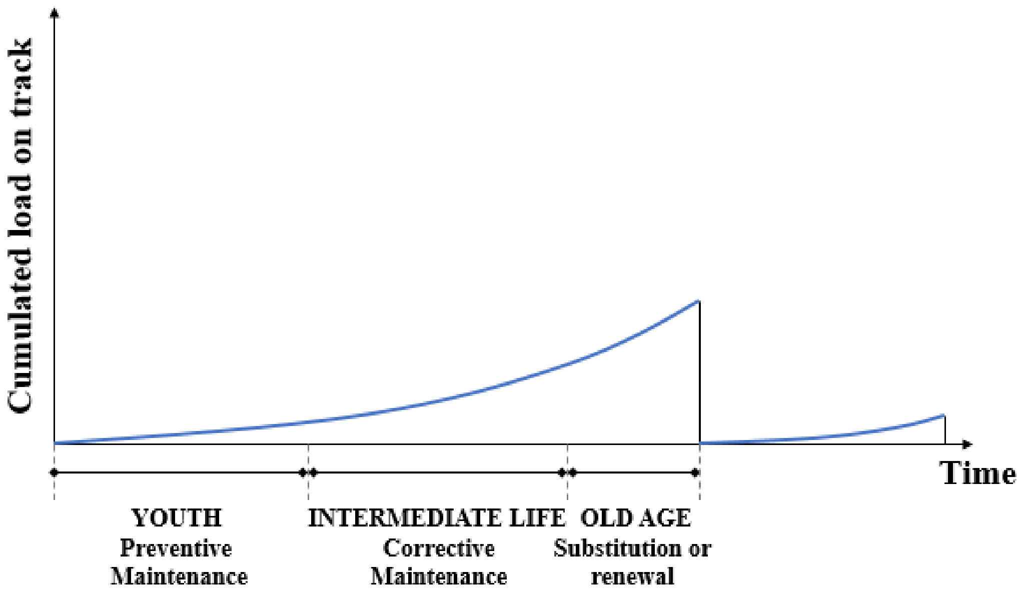

Figure 4 – Decay process and intervention strategies in a railway track

According to [45], three different time periods can be identified throughout the service life of a railway track, i.e., the youth, the intermediate-life and the old-age (*Figure 4*).

More specifically, during the youth stage the track is subject to significant deterioration due to expected infrastructure settlements. Preventive maintenance is therefore fundamental to avoid an early sharp structural decay. The intermediate-life is the period when corrective maintenance (i.e., rectification of the alignment or substitution of unsuitable materials) is applied to mitigate the deterioration and maintain the safety standards of the track up to an acceptable level. Finally, the old-age is the stage approaching the end of the service life of the track, when higher decay is expected to take over. The track components must here be partially or fully replaced in case the track does not comply with the appropriate quality standards [45].

It is worthy of mention that the track-bed components are non-renewable materials. Accordingly, an accurate and timely monitoring of the ballast condition allows to intervene before a decay is completely formed to adapt different techniques at the specific decay type. This approach results as less demanding in terms of the operations required for maintenance, as well as in terms of consuming a lower amount of non-renewable materials.

Currently, various techniques allow to perform a sustainable monitoring of the railway substructure by detecting the ballast decay at both the network and the local level. These methods can be roughly sorted into mechanised and non-mechanised.

Among the non-mechanised methods, the "through packing" approach is one of the most popular [46-48]. However, despite of its accuracy, maintenance is generally carried out through various mechanised techniques, taking over manual tasks widely performed by track teams in the past [9]. A manual maintenance of a rail track requires in fact ten times the man-hours demanded by a fully mechanised process, on average [49].

Amongst the mechanised techniques, tamping is typically carried out for prevention and correction of track geometry issues (i.e. sinking of the sleepers), whereas grinding is conducted in case of rail surface deteriorations [50]. Stages of tamping are discussed by [19] and displayed in *Figure 5*.

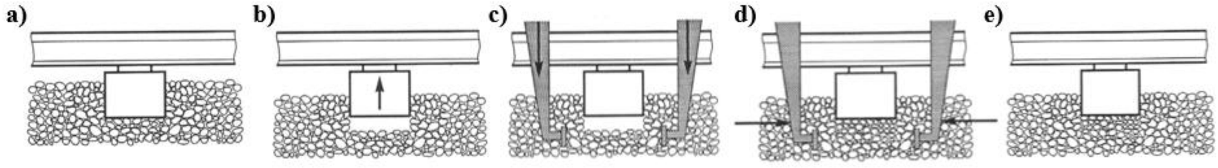

Figure 5 – Tamping activities

Specifically, these consist in: (a) the track and the sleepers are set in an incorrect position prior to tamping initialisation; (b) the rails and the sleepers are raised by the tamping machine to a required level, thereby creating an empty space beneath the sleepers; (c) the tamping tines are inserted into the ballast at both sides of the sleeper; (d) a pressure on the ballast through the tamping tines towards the created void, hence retaining the correct position of the rail and the sleeper; (e) removal of the tamping tines from the ballast and repeating the operation on the next sleeper.

3.2. Assessment techniques for railway infrastructure management

Based on the existing literature, various techniques have proven successful in assessing the condition of the track ballast components. In general, these techniques can be grouped into destructive and non-destructive, depending on their invasiveness to the structure. Although destructive techniques are still widely adopted for monitoring the ballast layer and railway foundations, non-destructive testing methods are gaining popularity in recent years as they have proven effective in reducing costs of maintenance.

The following sections report the main techniques and their classification based on their productivity.

3.2.1 Destructive techniques

Conventional techniques are usually destructive, as they are mostly based on the evaluation of samples collected on the track. Their use can provide accurate information, although this is significant only related at the section where tests are carried out. In addition to this, they have poor time efficiency and they cannot provide a comprehensive assessment of the damage and its formation mechanisms in the ballast and sub-ballast layers, but rather an indication about the decay conditions. These techniques typically include visual inspections, selective drill approaches and the dig-at-interval methods [11]. In view of the complexity of conditions in railway substructures, rapid, dense and integrated assessment techniques are therefore required. In this regard, non-destructive methods are nowadays preferred over conventional destructive techniques as they can provide more rapid and effective inspections at lower costs.

3.2.2 Non-destructive techniques

Various technologies with different data coverage and productivity performance can be listed for the assessment of ballast conditions (*Table 3*). In the following sections, these technologies are classified based on their data coverage and productivity features and a summary description for each of them is provided.

Table 3 – Non-destructive techniques classification

Technique	Standard/ Guideline*	Data coverage	Productivity (daily)	Resolution
Inertial	**G:** ASTM E950 – E950M (2018) [51]	Local level	Low (<10 km)	0.04 Hz
Acoustic and ultrasonic	**R:** BS EN 16729-1 (2016) [52]	Local level	Low (<10 km)	$10^{-3}÷10^{-4}$ m
Image-based	**R:** Guidelines [53]	Local level	Medium (10-20 km)	10^{-2} ÷ 1 m
Optical-based	**G:** Guidelines [54]	Local level	Medium (20-50 km)	10^{-4} m
Electromagnetic	**R:** BS DD ENV 50121-1 (1996) [55]; **G:** ASTM D6087 (2008) [56]	Local level	Medium (30-70 km)	$10^{-2}÷5×10^{-2}$ m
Satellite remote sensing	**G:** ASTM F2327 (2015) [57]	Network level	High (>100 km)	10^{-3} m

*Standards/Guidelines are general (G) or railway related (R)

3.2.2.1 Low productivity techniques

Inertial methods

Inertial methods can be used as an indirect measurement of the decay of ballasted layer and they rely on a double integration of the acceleration value collected by accelerometers. As an example, the vertical position of a wheel can be calculated via a double integration of the acceleration from the axle-box [58], since the wheel is continuously in contact with the rail (*Figure 6*).

Within this context, given the regularity of the surface of a sound rail, these methods assume that unexpected accelerations of the convoy wheels are associated with the presence of defects in the rails that, in turn, may be caused by structural problems in the ballast layers. Accordingly, aim of these models is to evaluate rail irregularities and search for the transfer function to relate input and output functions in the frequency domain [59]. The solution is then transformed into the time domain by implementation of the inverse Fourier transform.

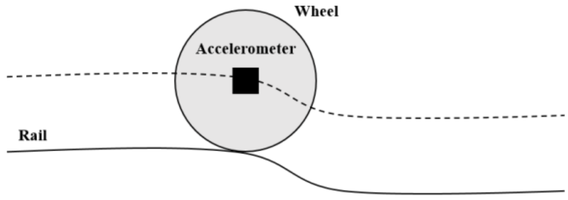

Figure 6 – Layout of inertial track measurements at the longitudinal level

<u>*Acoustic and Ultrasonic Techniques*</u>

Similarly to the inertial methods, acoustic-related methods can be applied to indirectly detect decays in ballast layers by inspecting the conditions of the rails. In terms of their working principles, the acoustic and ultrasonic techniques are based on the transmission of an acoustic source pulse to the rail surface and the reception and amplification of thr recorded pulse (*Figure 7*). This allows to measure the time elapsed with an accuracy of ± 1%. As the velocity of waves in a medium is dependent on its elastic properties and mass, these can be estimated by knowledge of the mass and the wave propagation in the medium [60, 61, 62].

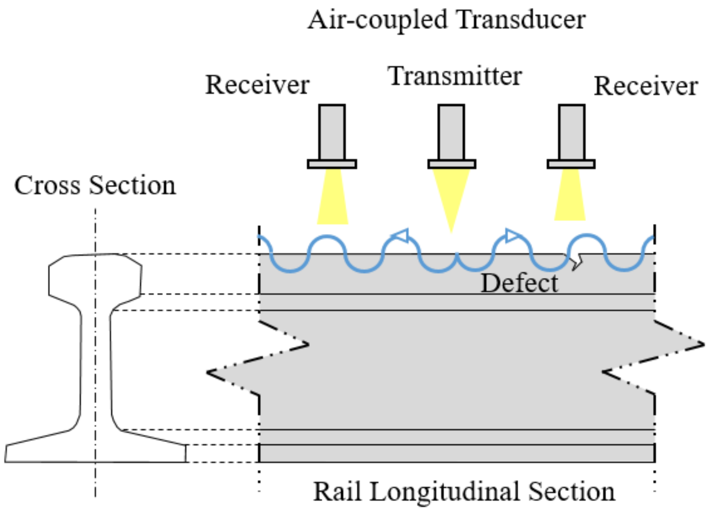

Figure 7 – Illustration of the air-coupled guided wave transducers

3.2.2.2 Medium productivity techniques

<u>*Image-based methods*</u>

Since traditional visual inspections are time-consuming, laborious, and highly dependent on the interpretation of the operator, automatic image-analysis algorithms have been proposed for the inspection of the superstructure (e.g., rails and sleepers) and the ballast layer. Actually, only few contributions are reported in the literature about using computer vision technology in railway maintenance [63]. In the research presented by [63], the purpose of an automatic rail inspection system was aimed at detecting sleepers and/or the fasteners, from real images collected through a digital camera. In [64], a system for the automatic detection of external material on the ballast surface was presented. In addition, [65] reports an investigation carried out at the laboratory scale into the railway ballast aggregates' properties based on an image-analysis algorithm (*Figure 8*).

Figure 8 – Plan view of ballast aggregates in a laboratory test scenario. (a): the raw picture collected with a digital camera. (b): the binary image obtained from the proposed image analysis algorithm [65]

<u>*Optical-based methods*</u>

Optical methods are typically based on the use of optical fibre sensors (OFSs), which are being increasingly used in civil engineering applications [66]. These systems are composed of an optical source exciting a transducer through a fibre optic cable. A schematic system of OFS is illustrated in *Figure 9.*

OFSs have many advantages as opposed to other conventional sensors. Amongst others, we can mention the contained dimensions, light weight. a low sensitivity to corrosion effects and EM interferences, and a general high reliability of measurements in view of the sensors being embedded directly into the structure/infrastructure [66, 67].

In addition to the above, [68] reported a wide spectrum of measurements associated with use of OFSs e.g., strains, vibrations, electric, acoustic and magnetic fields, accelerations, rotations, pressure, temperature, linear and angular positions, and the measurement of other important physical and chemical factors.

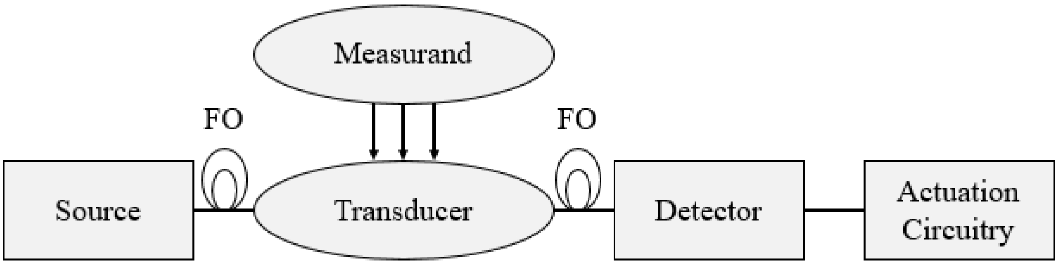

Figure 9 – A schematic system of OFSs

<u>*Electromagnetic techniques*</u>

Working principles of these methods stem from the electromagnetic (EM) theory and the material constitutive relationships, and they rely on the use of the radar technology (*Figure 10*). Among these methods, GPR is becoming popular due to its efficiency and reliability. GPR is a non-invasive, rapid and versatile technology that permits the investigation of long sections of the railway track (i.e., hundreds of kilometres) in a relatively short time, as the acquisitions can be performed at remarkable survey speeds. It provides high resolution images (data collected every few centimetres) and, due to its non-destructive principles, it can be repeatedly used over the same location to understand the evolution pattern of a decay.

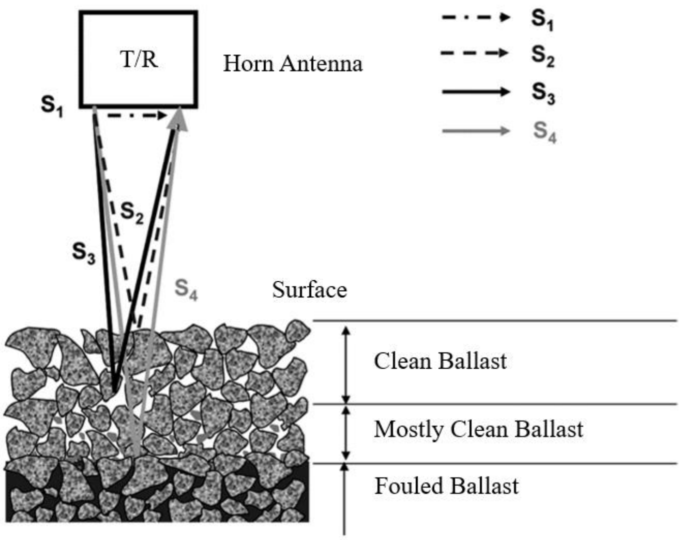

Figure 10 – EM wave propagation in a ballast section

3.2.2.3 High productivity techniques

<u>*Satellite remote sensing*</u>

Radar interferometry or interferometric radar is an effective remote sensing technique arising from space technology with applications into infrastructure monitoring (*Figure 11*). This technique can detect surface displacements using the phase information of a microwave signal back-reflected from scatterers on the ground. The scale and accuracy of detectable displacements depends on many contributing factors, including the nominal wavelength and resolution of the satellite sensors, and it can reach up to millimetres [69]. Research is currently focussing on finding effective solutions to issues related to the management of extensive databases, the harmonisation of datasets from multiple sensors and the integration between data interpretation methods from different areas of expertise [70]. Radar interferometry can be sorted two main areas, i.e., the real interferometry radar (RAR) and the synthetic interferometry radar (InSAR). Specifically, the InSAR technique was developed to overcome the limitations of the former through an azimuth independent by the slant range to the target, smaller antenna dimensions and relatively longer wavelengths [71].

The InSAR technique relies on the analysis of the variation of the signal phase between images collected at different times by an orbiting satellite [72]. Once the resulting interferogram is filtered from relevant noise, the phase variation can be related to the motion of the observed target on the ground, during the time-span separating the two acquisitions. Accordingly, InSAR represents an effective technique to monitor potential settlements in a railway network across multiple periods of observation.

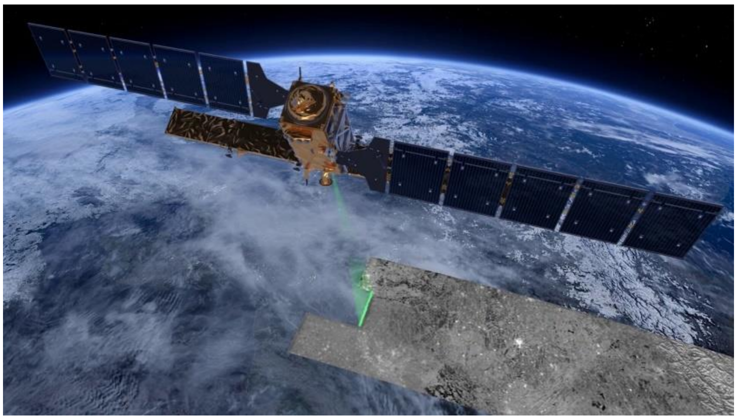

Figure 11 – A satellite remote sensing survey [71]

3.3 Basics and principles of GPR and InSAR methods

Amongst the above-mentioned techniques for railway infrastructure monitoring, the integration of the GPR method (electromagnetic techniques) and the InSAR technology (satellite remote sensing methods) appears to be the most promising non-destructive and rapid approach for detecting decays in railroad substructures. In fact, an integration of GPR at the local level and the InSAR method at the network level has the potential to allow for a timely diagnosis of hazardous events. Therefore, the integrated approach lends itself to be considered as an effective tool in the monitoring and sustainable maintenance of ballasted railways.

The logic of integrating InSAR and GPR information lies in the fact that these technologies are complementary. In fact, GPR can provide prominent information about the subsurface characteristics of the railway infrastructure, whereas the InSAR technique can detect effectively the ground displacements. According to the literature, it is possible to retrieve grading-related information with GPR (e.g., [65], [73], [74]), including the formation of ballast fouling (e.g., [18], [75], [76], [77]), amongst others. In case as-built ballast aggregate conditions change drastically and lead to formation of fouling, it has been proven that severe settlements can occur along the railway track [19]. In this context, use of the InSAR technology can stand as a fundamental monitoring tool to identify potential critical sections where to carry out more in-depth GPR inspections at an early-stage of development for the railway settlements.

Basics and principles of these two non-destructive techniques are discussed in the following sections.

3.3.1 GPR working principles

GPR principles relies on the physics of the EM field propagation described by the Maxwell's equations and material properties, defined in turn by constitutive relationships. In detail, the propagation of the EM waves depends on the three main electromagnetic properties of the host material [39]. Amongst these, the dielectric permittivity and the electric conductivity affect the wave velocity and attenuation, respectively, whereas the magnetic permeability does not influence the wave propagation in case of non-magnetic materials.

The frequency of the emitted signal and the type of material investigated are main factors affecting the penetration depth.

The most popular elements and factors investigated with GPR in railway engineering are [78]: i) the thickness of the structural layers ad foundations (ballast, sub-ballast, subgrade); ii) the degree of contamination of the ballast; iii) the ballast moisture content; iv) potential settlement areas.

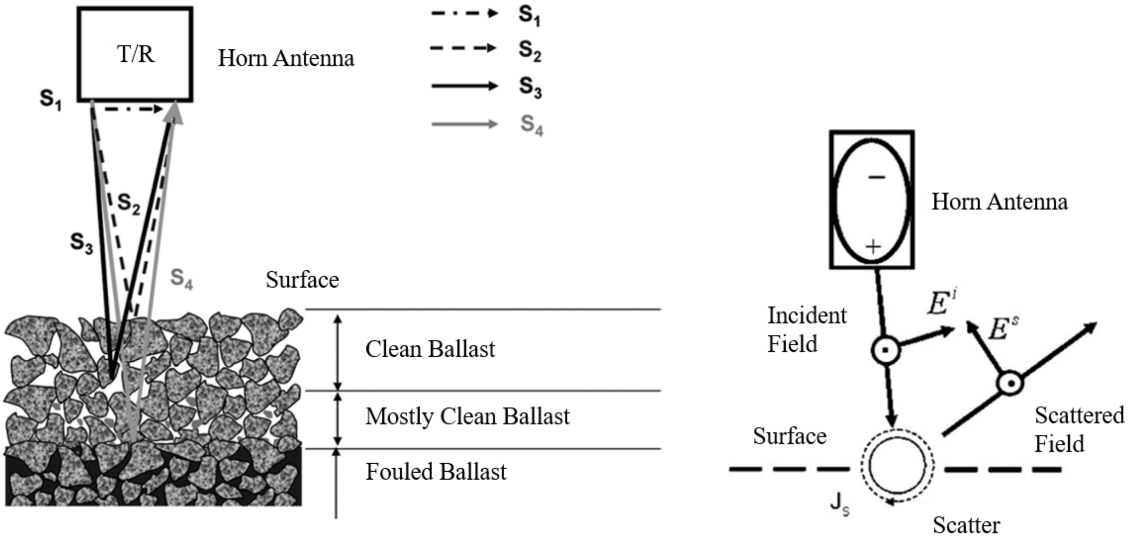

Figure 12 – Propagation of the GPR signal throughout railway ballast

Figure 12 shows the typical propagation pattern of a GPR signal through a ballast layer. The direct signal (S1) is the part of energy that is directly radiated from the transmitter to the receiver. Part of the signal (S2) is reflected at the surface of the ballast. Another portion (S3) is the energy generated due to scattering from voids in clean ballast. In case of a clear interface is formed between the clean and the fouled ballast or sub-ballast, a further portion of the signal (S4) is reflected from this interface.

Railway ballast is formed by uniformly graded coarse aggregates with large air voids [79], that may reach 30% in volume. Hence, the scattering response from the voids must be considered when dealing with the GPR acquisitions on ballasted tracks. In case of high-frequency antennas, scattering from voids may be the dominant factor when wavelength of the signa is coherent with the size of the air voids. The variation in the scattering pattern is in fact dependent on the size of the scatterer compared to the incident wavelength [73]. As the ballast becomes fouled, volumetric contents of the air voids in the material decrease. Accordingly, scattering responses in GPR data may be used as a parameter to estimate the most common fouling processes [73, 74].

3.3.2 InSAR working principles

The InSAR technique, or SAR interferometry, allows to detect displacements along the observation direction of the SAR satellite. It measures the variation in the signal phase between images collected on the same area at different time stages. The occurrence of a vertical or lateral motion at the infrastructure surface level (e.g., the ballasted railway in *Figure 13*) implies that an increase of the distance between the sensor and the target is generated. Hence, this affects the phase of the signal back-received by the sensor.

Differently than other satellite-based products, collection of SAR images does not depend on the atmospheric and lighting conditions and they allow the coverage of extensive areas, coherently with the footprint of the sensor. The progressive orbit of satellites permits the collection of regular and dense datasets in time, as opposed to on-site surveys that may be repeated only at very large time interval, due to the organisational and economic efforts required. Conversely, the acquisition and processing of SAR images are not necessarily linked with field operations. Hence, they do not constrain the closure of the infrastructure to the traffic, nor they are dependent from any operators on site. These factors have major economic and safety impact compared to other conventional monitoring techniques.

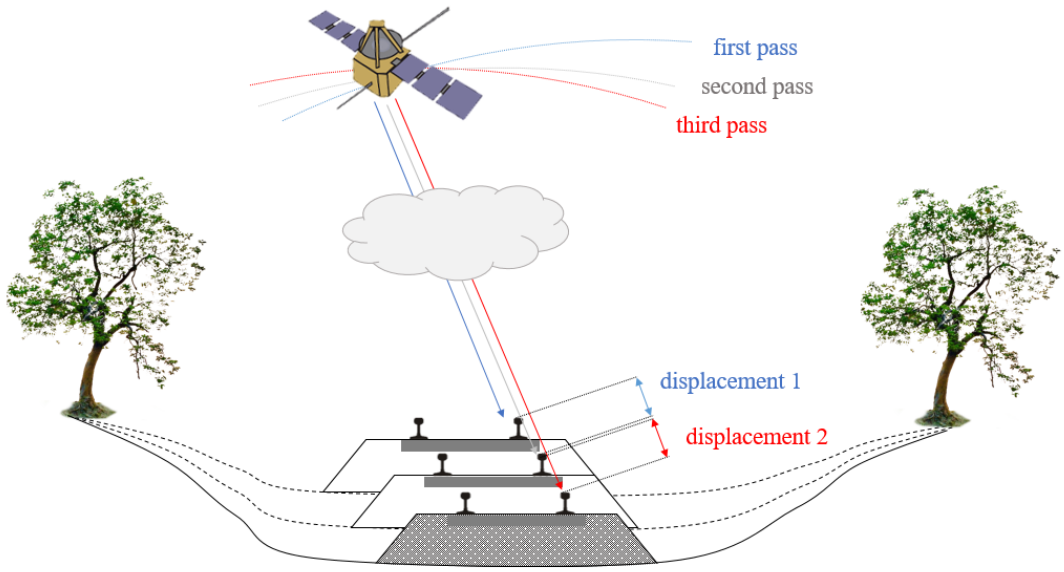

Figure 13 – Layout of a displacement detection by the InSAR technique. Several images are collected on the same area. Displacements are measured through the variation of the sensor–target distance across the images.

An interferogram is generated from the calculation of the phase difference between two SAR images in the form of numerical values ranging from $-\pi$ to $+\pi$. These are referred to a cell on the ground with dimension mainly dependent on the working frequency of the sensor. Therefore, through the observation of an interferogram it is possible to evaluate potential deformations on the ground during the survey time. However, such an analysis is a complex task, as the interferometric phase includes signal contributions of different natures, along with noise and decorrelation effects. To elaborate, the interferometric phase ($\Delta\varphi$) is affected by four principal factors, as reported in equation (6):

$$\boldsymbol{\Delta\varphi = \frac{4\pi}{\lambda}\Delta R + \alpha + t + noise} \qquad (6)$$

Where:

λ is the wavelength of the emitted signal; ΔR is the displacement in the line of sight (LOS); α is a phase shift due to different atmospheric conditions (e.g., moisture in suspension); t is the contribute of the local topography; whereas the noise parameter includes the temporal change in the scatterers as well as a noise component related to differences in looking angles and volume scattering.

The atmospheric contribution limits current applications of conventional InSAR methods and may inhibit accurate deformation monitoring. This occurrence is reduced with the application of the Multi-temporal InSAR technique, such as the "Persistent Scatterers Interferometry", whereas the processing phase provides a specific tool for the atmospheric phase contribution named "Atmospheric phase screen (APS)", which estimates and removes the atmospheric contributions.

In addition, the baseline parameters (i.e, the temporal and perpendicular baseline) are significant factors as they can contribute to the accuracy of the interferogram information. Larger baselines can influence the coherence value of the interferometric pair.

4. Research methods on the use of InSAR and GPR techniques in railway infrastructures

A review of research dealing with the application of InSAR and GPR techniques in railway engineering is reported in this section. Research methods are discussed based on the investigation scale (i.e., laboratory and numerical environments, test-site and real-world applications).

Therefore, an overview of main research in the above application areas is reported here. For each individual scale of investigation, the main applications of GPR to railway infrastructures are first reported followed by the applications of the InSAR technology coupled with the GPR survey.

GPR has been widely used in railway infrastructure monitoring. Applications include the evaluation of layer thicknesses [80], the investigation of the embankment stability [81], [82] the localisation of trapped water areas [83], the indirect estimation of the track modulus [84], and the detection of permafrost sections [85], [86], [87], [88]. A recursive analysis of GPR measurements collected routinely on the same infrastructure allows to predict the deterioration rate of a track substructure and to control the effectiveness of maintenance. This strategy can contribute to plan activities effectively with benefits in terms of costs and time [78]

In this framework, the InSAR technology has proven to be effective in detecting surface deformations at the network level. To this extent, an integration between InSAR and GPR allows to combine the versatility, the high resolution and the capability to infer the source of decays in the subsurface from GPR, with the provision of extensive multi-temporal information on ground settlements from InSAR.

Using this integrated data management approach in maintenance plan can lead to a more advanced concept of infrastructure resilience. In fact, a higher accuracy is expected to improve the infrastructure resistance to either major external events and ordinary decay. This is related to the provision of a more fast and precise interpretation of the active deterioration processes [89-91].

In this context, it is worth reminding that the application of InSAR techniques in the monitoring of railway networks is relatively recent compared to the use of the GPR technology, where first applications date back to 1980, as reported by [75]. However, the potential of using SAR imagery in the monitoring of civil engineering infrastructures has been reported in the last few years [27].

4.1 Laboratory-scale investigations and numerical developments

Ballast characterisation is one of the most addressed areas of research within the context of investigations conducted at the laboratory scale, as it well complies with the tests that can be developed with success on samples of material instead of entire real-scale set up.

In this regard, [92] has demonstrated that GPR can be used for the assessment of ballast, with a high correlation between EM response and fouling index. Moreover, [81] reports a GPR investigation of a railway subgrade with specific condition indicators supporting the data interpretation stage. More recently, a comprehensive GPR analysis has been presented for the EM characterisation of railway ballast aggregates. Several GPR antennas and frequency systems were used in a unique experimental setup to identify potential critical factors and most suitable survey configurations [93]. The importance of selecting proper central frequencies of the antennas according to the type of inspection in railways is also highlighted by [94], whereas in [95] the authors propose a multifrequency approach (500 MHz, 2000 MHz) to obtain a more comprehensive interpretation of the substructure.

Another topical research area relates to the assessment of fouling in ballast layers. Similarly to the previous application, GPR has proven relatively successful at the laboratory scale of the investigation [10, 18, 33, 79, 92, 95-98]. In [10], the authors present a comparative analysis of the relative dielectric permittivity of railway ballast with varying rate of fouling and humidity. The EM wave propagation velocity in ballast is inversely proportional to its dielectric permittivity and it is important for effective time-to-depth conversion of the GPR data. To this purpose, various studies [9, 74, 78, 99, 100] have attempted to experimentally calculate the EM wave velocity. In a recent study, [39] assess clean and fouled ballast using GPR through comprehensive laboratory experiments, signal processing and numerical modelling. A scattering amplitude envelope method based on the energy scattered from the voids between ballast aggregates has been also presented and used to identify clean and fouled ballast by off-ground GPR antenna systems [33, 79].

Water content estimation in railway substructures using GPR data is another major research area in the field [78, 101]. In [102], authors propose an investigation of the GPR response to evaluate railway ballast (different fouling and moisture conditions) at the laboratory and the real-life scales. The theory-based mixing model was used to verify the dielectric permittivity values obtained experimentally.

In terms of numerical developments, use of the numerical simulation has gained momentum in the past decade. This approach contributes significantly to reduce economic and computational costs [39]. To this effect, several studies have used the finite-difference time-domain (FDTD) technique for the simulation of the GPR signal [65, 97].

Effective collection of significant GPR data on the ballast underneath concrete sleepers and rails is another major area of research. Due to the masking effects of reinforcement bars, research has been done to limit these effects and collect representative data for the ballast. A focus on dedicated surveying procedures and antenna configurations was studied to consider the impact of ties and rails on the signal [95, 103, 104]. In terms of signal processing methods, [105] report a post-processing framework including, migration, horizontal scaling, stacking and background removal to minimise the effect of sleepers. A 40-trace running average is applied to the collected data by [106] to remove ringing noise from the sleepers. Lastly, a spectral-based method based on the error optimisation between i) the frequency spectra of the GPR traces collected at the sleepers' sections and ii) the frequency spectra of the traces acquired at the sections between two consecutive sleepers is proposed in [107].

4.2 Test-site investigations

Test-site investigations are typically carried out in ballasted track-bed prototypes built on purpose to perform dedicated GPR investigations. The advantage of these applications is in the possibility to control the track-bed boundary conditions and investigate into aspects, which are difficult to control in the real life.

Research has been reported for the assessment of the ballast conditions. [108] report GPR capability to identify track-bed ballast deterioration, in terms of variation of the relative dielectric permittivity, and detect the interface between ballast and formation. Large-scale track models and methods used for GPR data collection are also presented as the results of another test-site research. In more detail, the experiments were used to evaluate variations in the GPR response of the ballast in terms of density, water content, grain size distribution (GSD), and the variation of the fouling percentage content. To assess these parameters, a full-scale railway track was realised at the University of Massachusetts [109].

Regarding the ballast contamination, GPR was employed by [110] in a test specimen of a track-bed with multi-offset antennas to measure the signal travel time and the material dielectric permittivity of structural layers. The GPR study developed by [18] was carried out on model and actual railway tracks using several antennas to inspect three types of fouling materials. Antennas with central frequencies of 100 MHz, 500 MHz and 800 MHz were used and it was proved that highest quality results could be achieved with the 800 MHz antenna system.

Furthermore, with the aim of studying the pulse velocity variation under different ballast fouling conditions, tests in controlled conditions were carried out by [78]. A 4,0 × 0,5 × 0,5m wooden cell was built to simulate a ballast platform. The aim was to collect GPR data periodically over several months and to compare the effects of time on the data. The following parameters were studied: (1) pulse velocity in sands and ballast, (2) ballast-sand interface identification and, (3) detection of water concentration areas.

Finally, GPR surveys were also performed to assess the stability of the ballasted track, as reported by [81]. Two embankments affected by structural instability were investigated. Evidence of substructure instability causing settlement of rail tracks has been found as a result of the GPR surveys.

4.3 Real-life investigations

Thickness measurement of railway ballast layers and material quality evaluations are the main application areas of GPR in real-life railways.

In [105], the Swiss Federal Railways has inspected through GPR their railway tracks at regular intervals. Inspections were aimed at evaluating the thickness of the clean ballast, which was limited by subsoil material penetrating upwards into the ballast. Potential issues related to a transition from laboratory to test site environments are addressed in [111]. The authors outline most recent advancements in the acquisition, processing and interpretation of GPR data for a high-speed train instrumented with multiple-antenna GPR systems. The acquisition system combines GPR antennas, train tachometer inputs, GPS and video technologies for an accurate calibration of the GPR systems and the high accuracy of results. The system has proven effective at collecting a high-quality and very dense dataset (sampling interval lower than 5cm) at speeds of 100 km/h.

On the other hand, the dielectric properties of ballast have been investigated by [10] and [112], with a special focus on the effects of moisture content and fouling levels. [113] present an estimation of the dielectric permittivity values of good and poor-quality ballast materials, and their comparison in dry, moist and wet conditions. Signal travel time and material dielectric permittivity of the subsurface layers have been also investigated using multi-offset GPR antennas [114]. It was demonstrated that the GPR signal propagation velocity can sharply decrease of 10–30% from clean to fouled ballast conditions due to variations of fine particles.

A comprehensive study spanning from laboratory to real scale is reported in [102]. The authors discuss the use of the GPR method for the analysis of railway ballast with different fouling and moisture contents. Comprehensive laboratory experiments and field surveys are presented. In detail, field tests with 400, 900, and 2000 MHz GPR antenna frequencies were carried out on the same type of granite ballast used for preliminary laboratory tests.

As explained above, railway ballast may generate different electromagnetic scattering patterns when radiated by an EM field, depending on the specific fouling conditions. In this context, a field survey with multiple sets of 1 and 2 GHz air-coupled GPR antennas was performed in 2005 at the Transportation Technology Center, Inc. (TTCI) in Pueblo, Colorado [33]. The authors report that the 2 GHz antenna is more sensitive to changes by scattering. Furthermore, a study utilising GPR horn antennas to evaluate railroad ballast, sub-ballast, and subgrade conditions is reported in [77]. This research identifies a representative scattering amplitude envelope from the field data for implementation into an automatic data processing pipeline. Subsequently, 2 GHz data from 238 km of track were processed and the fouling conditions were automatically estimated from the GPR data.

In [115] the authors have employed a 1 GHz antenna to acquire survey data from the railway substructure. Data were collected at the centreline and both sides of the rails for comparison purposes, under the assumption that significant variations between the acquisitions may indicate instability at the foundation level.

Moreover, a geophysical investigation was carried out by [106] following the failure of a major railway embankment in Ireland. The embankment was inspected using GPR, electrical resistivity tomography (ERT), multichannel analysis of surface waves (MASW) and geotechnical testing. A significant variation in the thickening of the ballast layer in the vicinity of the failure location was observed using GPR, confirming an ongoing geotechnical instability issue.

Finally, several studies have used GPR on railway infrastructures to investigate reflection patterns in the signal and their link with structural elements of the railway. To this extent, GPR was found to face disturbance noise in the field, including high radio-frequency interference from railroad communication and automation systems, and strong reflection values coming from the rails. In the study developed by [116], special techniques were used to remove these interferences and limit strong clutter effects from rails. Short-time Fourier transform was therefore applied to infer information about the fouling.

Research from [107], [79] investigates the influence of concrete railway sleepers on the GPR signal. A main objective was to propose a data processing framework to filter out the effects of concrete sleepers on the GPR signals with compound information.

As real-scale tests allow the possibility to investigate entire railway section or even the full network, the InSAR technique becomes of great interest in monitoring the occurrence of track settlements and analysing the evolution pattern of distresses. Within this context, a real-life integrated application of InSAR and GPR is presented in [117], where the authors have investigated a railway section located in Puglia, Southern Italy. Specifically, a total of 57 SAR images collected in X-Band frequencies by the COSMO-SkyMed mission were acquired and processed by an interferometric procedure. As a result, the application of InSAR allowed to detect potential critical spots where the railway track was subject to settlements. This was instrumental to plan detailed GPR tests, which in turn were useful to identify the causes of distress. Same authors [118] proposed an integration between the GPR and the Interferometric InSAR techniques for the monitoring of transition areas at rail-abutment sections in railway bridges. To this purpose, a railway bridge located in Italy was inspected. GPR was used to achieve subsurface structural details and to detect any potential issue related to construction. InSAR analyses were mainly focussed to monitor subsidence at the rail-abutment transition area. Subsidence was found at both the areas of transition, proving that the proposed integrated approach can effectively assess the structural integrity of railway bridges.

In regard to applications about the integrated use of InSAR and GPR technologies, [119] report an overview on the data-fusion approach between the InSAR and the high-frequency GPR techniques. The study aims at evaluating solutions to compensate technology limitations of individual techniques based on a data-fusion approach.

5. Benefits of network-level satellite remote sensing and NDT monitoring

It is known that despite the advantages of suing ballasted rail tracks, rapid decay of ballast material can exacerbate costs of maintenance for the track. Rail track maintenance and repairing require major investments from asset owners to ensure proper serviceability of the railroad network. Based on available statistics, €50.000/km of tracks are the average annual maintenance and renewal (M&R) expenditures in West-European networks. Therefore, it is essential to monitor effectively each individual railway element and pursuing proper maintenance standards [120].

Several analytical models for railways can be used to achieve effective and efficient maintenance. In this framework, decision support systems (DSSs) integrating computational maintenance optimisation models can be used [121]. DSSs can assist asset managers in making more informative decision and find a balance between budget constraints and compliance with other major requirements.

Based on the benefits that can be achieved by an integration between satellite remote sensing and NDT technologies, a railway infrastructure management system is introduced in this section (*Figure 14*) with the aim to optimise railway track maintenance and renewal activities. The proposed approach is developed based on the provision of inventory data, built up in terms of identified railway network elements and as-built information. It is characterised by two concurrent routine monitoring stages developed at two data coverage levels, the local level for NDT and the network level for satellite remote sensing techniques. To elaborate, amongst the NDT methods, GPR is the technique that best fits for an integration with satellite remote sensing technology, as it allows inherently to collect more accurate information about the causes of distresses at the local scale. Remote sensing technologies are instead used to assess the entire infrastructure network in terms of ongoing geotechnical/geodynamic processes, with a high productivity (>100 km per day) permitted by the scale of the analysis.

In case critical sections are identified, targeted inspections can be carried out with dedicated NDT techniques with the aim to build a more comprehensive information system on the type and scale of the developing distress at the identified infrastructure sections. The information obtained at this stage can form the base of prediction models for distress evaluation, leading to assess whether maintenance or rehabilitation are required, and what priority level must be allocated to the identified intervention. Sections without critical spots are subject to new screening loops until the outcome turns positive.

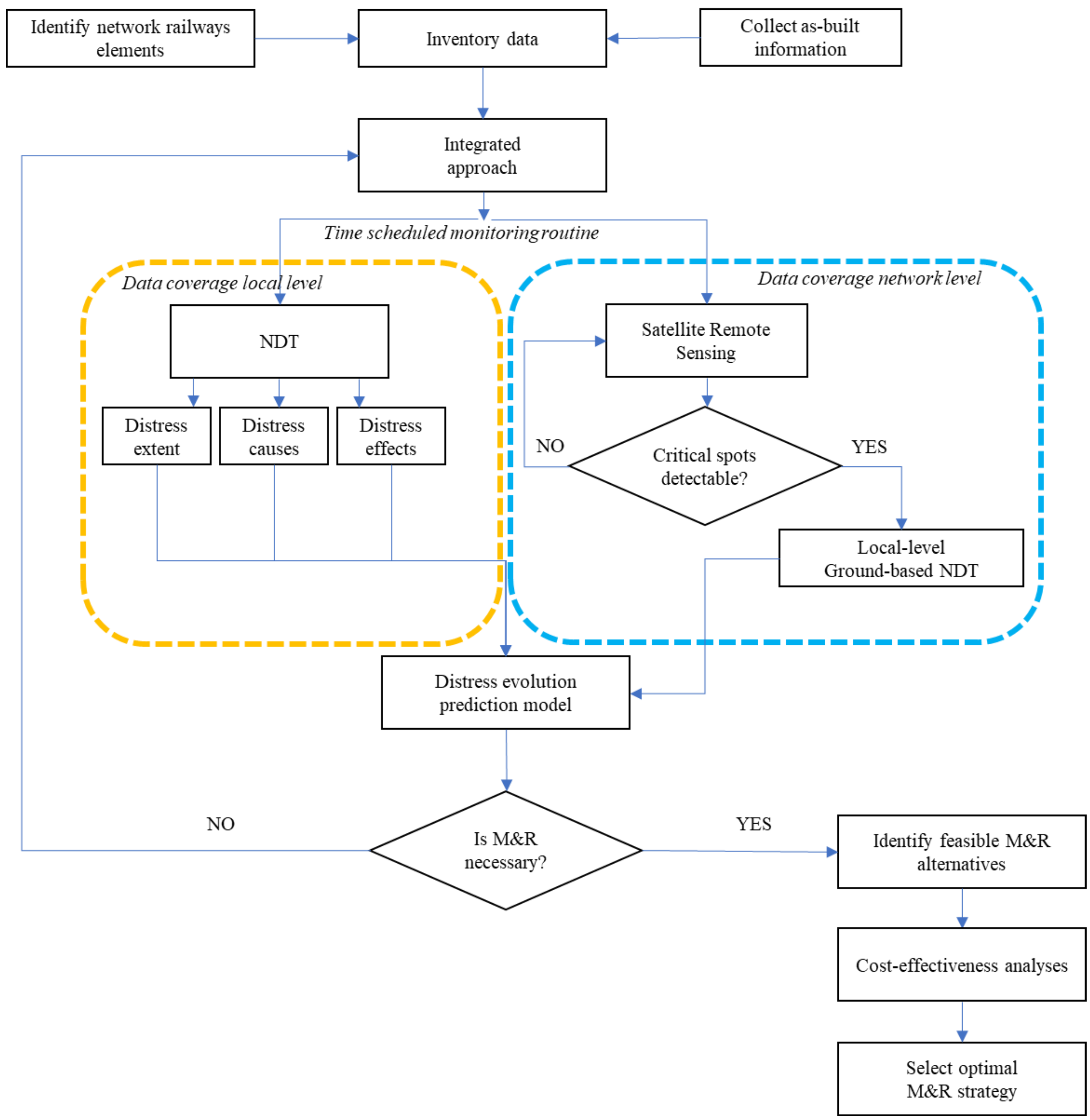

Figure 14 – The proposed railway infrastructure management system

In parallel with remote sensing technologies, ground-based NDTs working at the local level are used with a low productivity (that can reach a productivity of approximately 70 km per day). The main scope of this stage is to assess any potential distress in the infrastructure in terms of extent (e.g., sections in the asset with a low bearing capacity), causes (e.g., the presence of fine materials within the subbase course), and effects (e.g., low stiffness spots observed from deflection-based tests) that cannot be detected by satellite remote sensing.

This information is therefore integrated into an overall prediction model for the evaluation of distresses, which returns a scale of priority of the maintenance and rehabilitation activities for individual assets of the railway network. In case none of the information leads to the conclusion that M&R actions are required, the integrated approach is performed again following the time scheduled monitoring routine, until variations of the stable conditions are detected and concerning interventions are identified.

In case the need for an intervention is ascertained, the provision of several alternative M&R actions is assessed based on the compliance with safety requirements and economic constraints. For each of the alternatives, a cost-benefit analysis is performed, leading to the selection of the optimal strategy of M&R intervention.

Benefits of this integrated approach is demonstrated by several applications carried out in the past [106], [118], [119] demonstrating the effectiveness of a combined use of the InSAR technology and the GPR method. The findings from these studies suggest that use of an integrated approach can characterise the railway ballast deterioration more comprehensively. In fact, use of complementary InSAR and NDT methods can assess the ballasted track-bed conditions more accurately and, parallel to this, it can pinpoint the causes of the deterioration based on individual characteristics of specialist NDT methods.

To understand the role of the proposed railway management system, the discussion must therefore be broadened out to the maintenance concept. In fact, according to [122], a preventive-oriented policy for maintenance can be divided into time-based, condition-based and predictive maintenance (*Figure 15*).

Time-based maintenance involves cyclic activities of inspection and survey. In its implementation, the time interval between an operation and the following plays a key role. The operation time definition is based on reliability law of the element. Therefore, a time-based maintenance requires collection of statistical data on the failures that, along with the indications from manufacturers, allow to determine and design the time interval.

Conversely, a condition-based or predictive approach relies on the verification of conformity by measurement, testing, detection of the element characteristics and, hence, it allows to operate when the element requires maintenance. The main difference between the two approaches is that condition-based maintenance is based on the identification of decay symptoms prior to their appearance, whereas predictive maintenance is based on an estimation of the residual life of the infrastructure system.

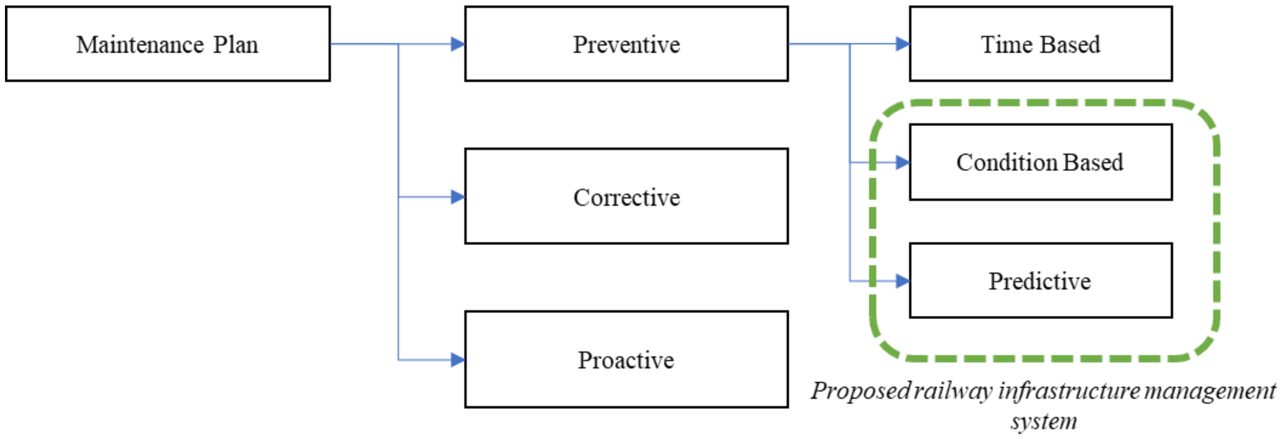

Figure 15 – Ordinary maintenance plan framework [122]

The proposed integrated approach including satellite-based surveys at the network level and the ground-based non-destructive detection of critical sections at the local scale, well fits into the above process as an effective predictive maintenance system.

It is worthy to distinguish two main stages of the system, based on their application time. A first phase relates to the beginning of the application, whereas a second phase starts when the methodology reaches its full productivity regime. In fact, in the first period after the application of the method, a limited database is available for the interpretation of the conditions of the asset. In particular, while the series of data collection are limited in time, only late-stage and rapidly evolving distresses can be detected. Accordingly, within the first phase, the outcome of this approach mainly fits with a condition-based maintenance, as opposed to a predictive maintenance.

Size of datasets of the collected information can increase by repetition of the surveys, and it allows the methodology to reach its full capacity. This condition permits to assess the trend of deformations and distresses. Therefore, the method is here in the condition to timely predict the genesis and the evolution of defects in ballasted tracks. At this stage, the proposed methodology, from now on referred to as “optimised”, becomes a totally predictive tool as a condition-based maintenance is required in case of unexpected events only, such as major natural events or traffic accidents. Indeed, starting from the first application of the method, the increasing dataset built from both the satellite- and the ground-based surveys forms the basis for the development of more robust and reliable distress prediction algorithms. These have the function to detect potentially dangerous decays at their very early stage of development.

Accordingly, three possible maintenance approaches are identified: i) time-based maintenance; ii) condition-based maintenance; iii) optimised condition-based. All these approaches aim at the highest reduction of the maintenance-related costs, at the long term.

In regard to the time-based maintenance, costs are due to several cyclic activities, such as tamping, ballast cleaning and ballast renewal [123]. These interventions, which are typically very costly as they involve all the railway track components, are regularly scheduled regardless the actual state of decay of the asset.

Conversely, main benefits of the condition-based maintenance are financial. In fact, this approach is based on inspections and tests that allow to apply maintenance interventions only where required, i.e., when the service conditions of the infrastructure are highly affected. This method is thereby effective in reducing maintenance-related costs compared to the time-based approach, increasing the operational availability of maintenance machines due to a more limited time of use and improving safety by limiting scale and severity of failures. An effective planning can save on maintenance costs and resources and it affects the safety and operational efficiency of the maintenance activities [124]. According to literature, condition-based maintenance typically generates savings ranging between 90% - 95% with respect to the costs of the time-based maintenance [125-127]. However, as a limitation of this approach, a separate analysis of the survey outcomes may fail in detecting decay trends, especially in case an accurate comparison between consecutive inspections is lacking. To elaborate, this might stand as a critical issue at the very first application of the condition-based maintenance, when previous surveys are missing and it is therefore impossible to retrieve information on the evolution trend of the distresses.

In view of this, an optimised condition-based scenario stands as an improvement of the previous maintenance approach, as it allows to minimise costs and maximise benefits in terms of operational safety and sustainability of the activities. Indeed, the integration of ground-based surveys with space-born surveillance permits to rely on back-dated time-series of subsidence in the area of interest. These are crucial to obtain a full knowledge of any potential geotechnical issue affecting the asset at the network level, that could be neglected without using this retroactive analysis approach. Furthermore, an initial backward inspection in time allows to recognise previous maintenance interventions conducted on the network and assessing their effectiveness. Accordingly, the optimised approach improves upon the time required for condition-based methods to be effective, as it allows the use of algorithms for the prediction of decay evolution from the first application (time-zero).

Therefore, this strategy and conceptual framework can stand as a viable solution for asset owners responsible for maintenance in planning interventions to limit effectively sources of decay at their early stage of development. This can positively impact financial and ecological aspects related to the infrastructure management process.

6. Conclusions and Final Remarks

This paper presents a review on the use of the Ground Penetrating Radar (GPR) and the Interferometric Synthetic Aperture Radar (InSAR) methods for the sustainable monitoring of railway infrastructures. The paper especially focuses on efficiency aspects of the NDT methods and envisions a more proactive approach for maintenance planning in this sector.

An overview of main issues from the inspection and maintenance as well as the track deformations is initially reported. Main types of deformations occurring in ballasted railways are discussed, highlighting the impact of fouling as a major source of failure and pointing out that an early detection is fundamental to limit future costs of intervention and risk of potential accident events. Specifically, it has been observed that the amount of fouling in a ballasted railway has been characterised and quantified using experimental and theoretical indexes. Methods for the evaluation of the track geometry have been sorted into conventional and non-destructive, and classified based on their productivity. Within this context, satellite remote sensing and non-destructive techniques have emerged as the most flexible, effective and sustainable. Furthermore, it was emphasised the relatively easy integration between GPR and InSAR measurements. A review on main research methods for an integrated use of these technologies in railway infrastructure monitoring has been presented, with examples given at the laboratory scale of investigation as well reporting real-life investigations.

Amongst others, the use of data-fusion methodologies involving the GPR and InSAR techniques has emerged as a new challenging area of development. To elaborate, training datasets collected from both the techniques across limited sections of the infrastructure can be used for the development of fine-tuning algorithms for extensive applications at the network level. This can allow a recurrent use of the technology with the highest "land coverage/data collection time" ratio (i.e., InSAR) and minimise the use of more time-demanding techniques (i.e., GPR).

In the last section of the paper, a conceptual framework based on an integrated approach including satellite-based and ground-based investigations is proposed, where network and local level information can be merged for the detection of critical sections and the implementation of a more advanced predictive maintenance system. The application of the proposed approach has different benefits. These can be financial, e.g., for railway companies and operators due to the totally predictive nature of the tool, environmental and ecological, related to a lower use of non-renewable materials and resources. Area of development and concentration for the proposed approach are in the need of a central railway management system to map railways both at local and network levels and the requirement of a dataset of satellite-based information for the development of more robust back-dated time-series analyses.

It is important to mention that the proposed monitoring framework is part of a new research project where the authors are currently involved and – to the best of our knowledge – new research is still to be explored in this area of railway engineering science.

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