IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received August 2, 2019, accepted August 10, 2019, date of publication August 15, 2019, date of current version August 30, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2935470

Towards Prognostic and Health Management of Train Wheels in the Chinese Railway Industry

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This work was supported in part by the Ministry of Education, School of Traffic and Transportation Engineering under Grant 2016YFB1200503-03 and Grant 2017YFB1201103-02.

ABSTRACT Condition-based maintenance is a more advanced maintenance strategy, owing to reducing inspection and maintenance costs and improving the reliability of targeted assets. The maintenance strategies in the Chinese Railway industry are transforming from plan-based to condition-based, which has heightened the need for the completion of relevant research. This study proposes an experience-based health status evaluation method for train wheels, which considers factors in the wheel manufacturing process, operational process and maintenance process. The manufacturing factors are indicated by material properties and press-fitting influence factor, while operational and maintenance factors are indicated by wheel diameter and damages. Based on the health evaluation values, a decision-making function is constructed to divide wheels into four categories: fine, attention, pre-alarm and scrapped. Finally, the PHM + Wheel system is developed based on the proposed health evaluation method to provide support for maintenance strategy. The PHM + Wheel system has been practically applied to the Chinese Railway industry with adequate feedback received.

INDEX TERMS Prognostic and health management, train wheels, health status evaluation, prognostics.

I. INTRODUCTION

The Chinese railway system has experienced considerable advancements in the past decades due to China's vast territory, large population and the overgrowing demand for public transport. According to the 2008 Mid-and-Long-Term Plan of Railway Network, the railways in China will lengthen to 120,000 km by 2020. Numerical railway equipment has been manufactured and implemented, and so the scale continues to rise. According to the official report, there are more than 20,000 locomotives and more than 300,000 train wheels in service across China. However, it is inevitable that over time, this aging equipment, including train wheels, will be exposed to harsh stress and tough environmental conditions. Thus, maintenance for such a vast reserve of equipment is a vital prioritization.

Historically, three types of maintenance strategies are developed to ensure the safety of railway industrial equipment [1], [2]. Firstly, the maintenance happens only when industrial equipment breaks down, hence malfunction cannot be prevented in advance. Sudden failure can cause high levels of machine downtime and maintenance cost. Second, the plan-based maintenance strategy, in which maintenance is performed at a periodic interval regardless of the health status of equipment [3]. Although some potential problems can be solved before causing failure of equipment, the plan-based preventive maintenance also calls for a great amount of finance and workforce input due to unnecessary maintenance tasks. To conduct this situation, condition-based maintenance is extensively studied and applied in a wide variety of mechanical systems [4], [5]. Condition-based maintenance is recommended when there is evidence of any abnormal behavior based on information collected through condition monitoring. According to the literature [6], 99% of equipment failures can be indicated by certain symptoms before they occur. Consequently, condition-based maintenance is considered as a more efficient and ideal maintenance strategy that can not only avoid catastrophic failures, but also reduce the life cycle cost of equipment [7].

As an important technique that supports the condition-based maintenance, the prognostics and health management (PHM) system provides a novel solution that evaluates the

The associate editor coordinating the review of this article and approving it for publication was Xiangxue Li.

health status (HS) and remaining useful life (RUL) of industrial equipment [8]. With the estimated results, a smarter maintenance strategy can be developed, which brings about cost reduction and an availability of industrial equipment increase. Previously, the PHM has been studied in many fields, such as aerospace, electrical system, navigation, complex system, and military et al. [9]–[13]. However, to our knowledge, little consideration has been paid to the application of PHM in railway industrial equipment, especially the train wheel. Only a few studies can be found, which have made efforts to develop the condition monitoring techniques and the HS evaluation method of wheels for PHM purpose [14].

Principally, the present maintenance strategy in China is still plan-based, which induces a huge amount of unnecessary maintenance and related cost. Take the case of wheels, as one of the most important components of the bogie, they bear the load, guide the direction of the locomotive, and suffer a diversity of damage modalities such as cracks, fatigue, corrosion, scratch, and wearing [15]. According to the literature [16], [17], train wheel failures are the cause of half of all train derailments and costs the global rail industry billions of dollars each year. The redundant plan-based maintenance expenditure plays a key role in China, as approximately 319 million yuan (roughly $51.2 million) is wasted during a single year due to over maintenance of rail wheels. Therefore, it is compulsory to implement a scientific maintenance strategy of train wheels to avoid failure at a minimal cost. Condition-based maintenance using the PHM is urgently needed in the railway industry.

Prognostics model, which helps the decision making of maintenance, plays an important role in PHM system. Several studies on the prognostics model of wheels have been previously proposed. The prognostics models can be realized by two different kinds of methods, namely, model-based and data-driven methods. Model-based methods utilize mathematical models to describe the underlying failure of mechanisms or the degradation process of train wheels, such as the wheel/rail wear model [18], [19] and wheel-rail contact zones damage [15], [20]. On the other hand, data-driven approaches require no special understanding of the mechanics and propagation of damage. In this way, the degradation process and future state are deduced directly from monitoring data through machine learning or statistical methods [21], such as Bayesian analysis [22], deep learning [23], integrating learning [24], and data mining methodology [25], et al. However, the model-based and data-driven methods have their own advantages and disadvantages. For example, the model-based methods are not always accurate since they cannot handle the uncertainty in different contents. To overcome this problem, the most recent studies attempt to integrate the model-based method with data-driven method to overcome this problem [26].

Nevertheless, the present train wheel diagnostics models have some limitations. Due to the lack of effective state evaluation methods, current train wheel prognostic models are developed based on the failure data, as failure or fault events can be distinguished and recorded distinctly. However, it is argued that there will not be enough time to prepare maintenance if prognostics for failure are constructed. Thus, prognostics for states prior to failure might be more helpful in order to avoid accidents. For another, the wheel failure, in some of the literature related to train wheel diagnostics, is simply represented by the wheel diameter (i.e., assuming a linear degradation path of wheels) [27], [28]. However, besides diameters, the maintenance decisions of train wheels are significantly related to other factors, such as in the manufacturing process or fatal damages. In the entire life cycle of wheel, from manufacturing to operation and ultimately scrapping, a value of data can be obtained, yet a meager amount is used in current studies. A comprehensive health evaluation method of the train wheel will benefit the maintenance strategy of the PHM system.

To this end, this paper proposes a practical health evaluation method based on factors in the manufacturing process, operational process and maintenance process of the train wheels. Different from other data-driven methods and model-based methods proposed by previous studies, the method proposed in this paper is experience-based, which is mainly concluded based on the 20 years' accumulated experience and relative standards in the Chinese railway. One of the advantages of the method is that it works under the condition that the data-driven methods and the model-based methods cannot work due to the lack of sensing data. The manufacturing process, including production and press-fitting steps, determines the original status of a wheel. The operational process and maintenance process, including lost in diameter of wheels, determines the acquired status. Then, the method evaluates the RUL of wheels and a corresponding PHM system is proposed. Different from the previous methods that use complex algorithms, need large number of data to train, and are difficult to be used in engineering application directly, the health evaluation method and RUL evaluation method proposed in this study are quite easy and have been applied to the PHM + Wheel system of Chinese railway and received adequate feedbacks.

The rest of the paper is organized as follows: the health evaluation model is presented in Section 2. Then, an application of the proposed method in PHM system and case history is expressed in Section 3 and Section 4, respectively. Finally, the conclusions and limitations of this paper are conducted in Section 5.

II. HEALTH EVALUATION METHOD

The health evaluation method is proposed to evaluate the health status (HS) and remaining useful life (RUL) of train wheels. For the HS is not only influenced by the factors in service process after leaving factories, but also significantly related to the material properties and press-fitting processes. Thus, two types of factors (i.e., manufacturing influence factors and operational state factors) are considered to evaluate the HS and construct a decision-making function of HS, which divides the HS into four categories: fine, attention, pre-alarm and scrapped. For the RUL, the physical damage (i.e., normal wear and re-profiling) and wheel diameter are considered to construct the function.

A. HEALTH STATUS EVALUATION

HS is an important indicator that evaluates the health status of wheels and helps the decision making of maintenance. Considering that the manufacturing influence factors and operational state are independent to each other, the evaluation results of them are multiplied to obtain the HS value. Thus, the decision-making function based on HS evaluation is displayed in (1).

$$y = ky_x = \begin{cases} \text{fine}, & 75 < y \leq 100 \\ \text{attention}, & 50 < y \leq 75 \\ \text{pre-alarm}, & 0 < y \leq 50 \\ \text{scrap}, & y = 0 \end{cases} \tag{1}$$

where y is the health status value of a wheel, k is manufacturing impact factors, and y_x is operational state of the wheel. k and y_x are decomposed into indicators and formulated using the indicators based on the analytic hierarchy process theory [29]. The limitations of variable in the equations are decided based on the experience which has been accumulated for many years in engineering application.

Wheel manufacturing includes the production process and the press-fitting process. The influence of production process is represented by material properties. Although the material properties of all the wheels meet the standard requirements, different material properties still lead to the difference in performance. Meanwhile, the interference in the press-fitting process significantly affects the connectivity performance between wheel and axle (i.e., higher interference can lead to higher contact stress between wheel and axle). Hence, the wheel manufacturing determines the original HS of wheels and should be considered in the HS evaluation model. Because of the independence of the two processes, the two corresponding coefficients are multiplied to characterize the manufacturing influence coefficient, which is displayed in (2).

$$k = k_1 \times k_2 \tag{2}$$

where k_1 is wheel material properties influence factor and k_2 is wheel press-fitting process influence factor. The value of k_1 and k_2 are both within [0,1], and the models for them are detailed in the "Material properties" and "Press fitting" subsections.

Operational state is another aspect to evaluate the HS of wheels. Factors in the operational period impacting the wheel's HS mainly are diameter and damage. The original operational state value of a new wheel without damage is set to 100, then it will be deducted accordingly with the wheel's diameter and damage state change. In other cases, if the sum of the two-state indexes value exceeds the limit value 100, the wheel operational state takes zero. The wheel operational state magnitude model is displayed in (3).

$$y_x = \begin{cases} 0, & y_a + y_b > 100 \\ 100 - y_a - y_b, & y_a + y_b \leq 100 \end{cases} \tag{3}$$

where y_a is the wheel diameter state value and y_b is the damage state value. The effects of wheel diameters and different injuries on the magnitude of the operational state are detailed in the "wheel diameter" and "damages" subsections, respectively.

Additionally, it is a fact that the impact of different factors on the evaluation result is different and the different indicators which determine the factors also have different effects on the factors. To handle this problem, the expert evaluation method is used to evaluate the sensitivity of the indicators. According to the expert evaluation method, the impact of indicators is divided into seven categories: 0%, 2%, 5%, 8%, 20%, 50%, and 100%, where a higher score indicates a higher impact.

1) MATERIAL PROPERTIES

Production technique determines the material properties of a wheel, and the performance of each batch of wheels is not identical. In this paper, four indicators (i.e., chemical composition, mechanical properties, grain size, and non-metallic inclusions) are used to characterize the material properties of a wheel. Although the mechanical properties are determined by other three influencing factors, it is very difficult to describe the correlation between the mechanical properties and the other three influencing factors by using a mathematical model. Hence, they are assumed to be approximately independent to each other and the wheel material properties influence coefficient is depicted by the product of the four material property factors, which is displayed in (4).

$$k_1 = k_{11} \times k_{12} \times k_{13} \times k_{14} \tag{4}$$

where k_{11}, k_{12}, k_{13} and k_{14} are chemical composition coefficient, mechanical properties coefficient, grain size coefficient, and non-metallic inclusions coefficient, respectively. The range of value of each material property coefficient is [0, 1].

Furthermore, those four types of coefficients are determined by more specific factors. The factors and corresponding limited values are identified based on the long-term practical experience on Chinese railways. The specific factors and related models are briefly introduced as follows, and the experience values that determine the status of wheels are directly used in the model. Note that the experience values are values only feasible under low-speed condition (i.e., the speed of train is below 160 km/h).

a: CHEMICAL COMPOSITION INFLUENCE FACTOR

Besides the iron element, some other low-content elements also exist in the wheel steel and have a significant influence on the performance of steel. These elements could be classified into three categories: added elements, harmful elements, and residual elements. In detail, carbon, silicon, and manganese are necessary additions to ensure the orderly performance of wheels. Take the case of silicon, an appropriate amount of silicon in steel can strengthen ferrite, enhance strength, elasticity limit and hardenability, also improving the anti-temper softening structure. Sulfur and phosphorus are harmful residual elements, which can easily form sulfides and phosphides with metal elements, and aggregate in the final solidified part of molten steel to form segregation, such as FeS and Fe_3P. Chromium, nickel and molybdenum are residual elements, which usually generate in the smelting process, have a positive effect on improving the performance of wheels. For instance, chromium can form a continuous solid solution with iron, and develop a variety of carbides with carbon, which can boost the oxidation resistance, corrosion resistance, hardenability and toughness of steel. Hence, the chemical composition influence coefficient can be formulated as (5).

$$k_{11} = \begin{cases} 0, & k_{111} = 1 \text{ or } k_{112} = 1 \text{ or } k_{113} = 1 \\ 1 - k_{111} - k_{112} - k_{113}, & k_{111} \neq 1, k_{112} \neq 1 \text{ and } k_{113} \neq 1 \end{cases} \tag{5}$$

where k_{111}, k_{112} and k_{113} are the coefficients of added elements, harmful elements, and residual elements, respectively. k_{111}, k_{112} and k_{113} are determined by the contents of the elements it contains, which can be formulated as (6)-(8).

$$k_{111} = \begin{cases} 0, & 0.40\% < ys_{1-1} \leq 0.56\%, 0.2\% < ys_{1-2} \leq 0.4\% \text{ and } 0.6\% < ys_{1-3} \leq 0.8\% \\ 0.02, & \text{otherwise} \\ 1, & ys_{1-1} < 0.40\% \text{ or } ys_{1-1} > 0.56\% \text{ or } ys_{1-2} < 0.2\% \text{ or } ys_{1-2} > 0.4\% \text{ or } ys_{1-3} < 0.6\% \text{ or } ys_{1-3} > 0.8\% \end{cases} \tag{6}$$

$$k_{112} = \begin{cases} 0, & ys_{2-1} \leq 0.009\% \text{ and } ys_{2-2} \leq 0.012\% \\ 0.02, & \text{otherwise} \\ 1, & ys_{2-1} > 0.015\% \text{ or } ys_{2-2} > 0.02\% \end{cases} \tag{7}$$

$$k_{113} = \begin{cases} 0, & ys_{3-1} \leq 0.18\%, ys_{3-2} \leq 0.18\% \text{ and } ys_{3-3} \leq 0.048\% \\ 0.02, & \text{otherwise} \\ 1, & ys_{3-1} > 0.3\% \text{ or } ys_{3-2} > 0.3\% \text{ or } ys_{3-3} > 0.08\% \end{cases} \tag{8}$$

where ys_{1-1}, ys_{1-2} and ys_{1-3} are the carbon, silicon, and manganese contents, respectively; ys_{2-1} and ys_{2-2} are the sulfur and phosphorus contents, respectively; ys_{3-1}, ys_{3-2} and ys_{3-3} are the chromium, nickel and molybdenum contents in the wheel, respectively. Equations (6)-(8) indicates that, for a specific indicator, if its value is in the range of excellent performance, the corresponding influence coefficient is 0 (i.e., the indicator with value in the given range do not have impact on the evaluation result); if its value is qualified but not in the excellent range, the influence coefficient is 0.02 (i.e., the indicator with value in the given range have an impact on the evaluation result by 2%); otherwise, the wheel should be scrapped, and the corresponding coefficient of the lapsed indicator is 1 (i.e., the indicator with value in the given range have an impact on the evaluation result by 100%).

b: MECHANICAL PROPERTIES INFLUENCE FACTOR

The mechanical properties of wheels mainly consist of three types of indicators: tensile, impact and hardness. In general, tensile properties can be expressed by yield strength, tensile strength, elongation, and area shrinkage, reflecting the ability of the material to resist fracture, permanent deformation, and plastic deformation. In this study, tensile strength is used to characterize the tensile properties of wheels, which refers to the critical value of the transition from uniform plastic deformation to localized plastic deformation of tensile specimens. Impact toughness refers to the ability of a material to absorb plastic deformation work and fracture work under impact load, reflecting the fine defects and impact resistance inside the material. Hardness is an index to measure the resistance to plastic deformation of a material, which could be evaluated by the degree of local plastic deformation of the material surface. The higher the hardness of a material, the stronger resistance to deformation and better wear resistance. Similar as the model which determines the chemical composition influence coefficient, the influence coefficient of mechanical properties can be formulated as (9).

$$k_{12} = \begin{cases} 0, & k_{121} = 1 \text{ or } k_{122} = 1 \text{ or } k_{123} = 1 \\ 1 - k_{121} - k_{122} - k_{123}, & k_{121} \neq 1, k_{122} \neq 1 \text{ and } k_{123} \neq 1 \end{cases} \tag{9}$$

where k_{121}, k_{122} and k_{123} are the influence coefficients of tensile strength, impact, and hardness, respectively. The k_{121}, k_{122} and k_{123} are determined by following (10)-(12).

$$k_{121} = \begin{cases} 0, & 880 < T \leq 940 \\ 0.02, & 820 \leq T \leq 880 \\ 1, & T < 820 \text{ or } T > 940 \end{cases} \tag{10}$$

$$k_{122} = \begin{cases} 0, & I \geq 18 \\ 0.02, & 12 \leq I < 18 \\ 1, & I < 12 \end{cases} \tag{11}$$

$$k_{123} = \begin{cases} 0, & H \geq 270 \\ 0.02, & 250 \leq H < 270 \\ 1, & H < 250 \end{cases} \tag{12}$$

where T, I and H are the tensile strength of wheel rim, the impact energy of wheel rim at 20°C and the hardness at 35mm under tread, respectively.

c: INFLUENCE COEFFICIENT OF GRAIN SIZE

Material with larger number of grain size has finer grain, and better tensile properties, toughness, hardness. Besides, dislocations and intergranular slips can be more effectively prevented, and more energy will be required to fracture for the large grain size material. Thus, the grain size influence coefficient model can be formulated as (13).

$$k_{13} = \begin{cases} 1, & Z > 7 \\ 0.98, & 6 \leq Z \leq 7 \\ 0, & Z < 6 \end{cases} \tag{13}$$

where Z is the grain size of wheel rim.

d: INFLUENCE COEFFICIENT OF NON-METALLIC INCLUSIONS

Non-metallic inclusions are formed by a small amount of slag, refractory materials and reaction products entering the molten steel during the smelting process. Non-metallic inclusions can reduce the mechanical properties of steel, especially the plasticity, toughness and fatigue limitation. Non-metallic inclusions also promote the formation of thermally processed fibrous structures and banded structures in steel, giving the material an anisotropy. More importantly, the transverse plasticity can only be half of the longitudinal direction and the impact toughness will thus be greatly reduced in critical circumstances. The non-metallic inclusions in wheel steel are mainly divided into two categories: alumina inclusions and silicate inclusions. For alumina inclusions, the most common oxides in steel is Al_2O_3, which is a small refractory and high-hardness brittle inclusion produced by deoxidation of Al. The inclusions will not deform after hot processing, but are distributed along the processing direction, forming a short-line particle band, where the initial crack often forms. For silicate inclusions, silicates like ferrous silicate, manganese silicate and ferromanganese silicate are very common in steel, they are generally of irregular shape, coarse, and the source of crack initiation. Based on the width of the inclusions, both alumina inclusions and silicate inclusions could be classified into fine alumina/ silicate inclusions and coarse alumina/silicate inclusions. Thus, the non-metallic inclusions influence coefficient model is displayed in (14).

$$k_{14} = \begin{cases} 0, & k_{141} = 1 \text{ or } k_{142} = 1 \\ 1 - k_{141} - k_{142}, & k_{141} \neq 1 \text{ and } k_{142} \neq 1 \end{cases} \tag{14}$$

where k_{141} and k_{142} are the influence coefficient of alumina inclusions and silicate inclusions, respectively. k_{141} and k_{142} can be formulated as (15)-(16).

$$k_{141} = \begin{cases} 0, & FAI \leq 1 \; and \; CAI \leq 0.5 \\ 0.05, & otherwise \\ 1, & FAI > 1.5 or CAI > 1 \end{cases} \tag{15}$$

$$k_{142} = \begin{cases} 0, & FSI \leq 1 \; and \; CSI \leq 0.5 \\ 0.05, & otherwise \\ 1, & FSI > 1.5 or CSI > 1 \end{cases} \tag{16}$$

where FAI, CAI, FSI and CSI are the grades of fine alumina inclusions, coarse alumina inclusions, fine silicate inclusions and coarse silicate inclusions, respectively.

2) PRESS-FITTING

The axle interference has a great influence on the connection performance. Smaller interference may cause looseness when the axle rotates at a high speed. On the contrary, larger interference can lead to material damage during the press-fitting process, and the axle contact stress may exceed the allowable range in this condition. Therefore, the index of press-fitting process is expressed as a percentage of the axle interference from the diameter of wheel seat. It is suggested that the axle interference at low speed should be 0.08% - 0.15% of the diameter of wheel seat. Hence, the press-fitting influence coefficient model is formulated as (17).

$$k_2 = \begin{cases} 1, & 0.08\% \leq P \leq 0.15\% \\ 0, & P < 0.08\% \; or \; P > 0.15\% \end{cases} \tag{17}$$

where P is the percentage of the axle interference from the diameter of wheel seat.

3) WHEEL DIAMETER

If a wheel diameter reduced to a certain extent due to wear or re-profiling, the safety margin of the wheel will not be large enough to guarantee the safety of operation. As a result, wheel diameter limit is defined. Taking China's low-speed electric locomotive as an example, wheel diameter is limited to 1150 mm, when the diameter reaches 1160mm the wheel is close to being scrapped. Therefore, the wheel diameter state magnitude model is formulated as (18).

$$y_a = \begin{cases} 0, & d > 1160 \\ 80, & 1150 < d \leq 1160 \\ 100, & d \leq 1150 \end{cases} \tag{18}$$

where d is the wheel diameter.

4) DAMAGES

Wheels are invaluable moving parts of rolling stock. Such elements as the stress state, poor service conditions and defects in materials or manufacturing may cause various damages to wheels, which include surface damage, internal damage and falling blocks. When the damage develops to a certain extent, some adverse consequences will occur, such as the increase of wheel-rail force and wheel stress, and the bolts in bogies will become loose. The three types of damage mode might exist in wheels simultaneously, so the sum of their values is used in the overall damage state assessment model. The damage state magnitude model is displayed in (19).

$$y_b = \begin{cases} 100, & y_1 + y_2 + y_3 > 100 \\ y_1 + y_2 + y_3, & y_1 + y_2 + y_3 \leq 100 \end{cases} \tag{19}$$

where y_1, y_2 and y_3 are the surface damage state magnitude, the internal damage state magnitude and the falling blocks state magnitude.

a: SURFACE DAMAGE STATE MAGNITUDE

Wheel surface damage might cause strong impact between contacted wheel-rail, and drastic change of dynamic response of track system, which has a great influence on motion stability and service life of various components of vehicle-track systems. The form of surface damping can be roughly divided into four types: peeling, scratching, grinding and polygon. The peeling gives rise to high frequency running vibration of the train, which not only shortens the running quality, but effortlessly causes bolts of the bogie to fall off, adversely affecting the safety of train operation. Meanwhile, the peeling can increase workload of on-site re-profiling, reducing the service life of wheels and causes economic losses. Severe wheel scratches have the potential to cause high-frequency impact force which can be 3 to 4 times greater than normal. The equivalent stress of the dangerous section of axle also has the potential to be twice as high as that without scratches. With the high-speed rotation of wheels, the periodic impact of wheel scratches on the wheel-rail system will increase significantly, resulting in damage to components such as bearings and reducing the smooth operation of the train. As for the grinding damage, when a wheel is running on a curve, the contact stresses between the rail and the wheel rim, if between the rail and the lateral surface of the rim is large enough to exceed the yield limit of material, it will cause a cumulative plastic flow deformation of the metal at these locations. Wheel polygon can lead to an increase in the normal force of the wheel-rail system and deterioration of the vertical vibration of the wheel, causing produce bending vibration of the axle, which may further aggravate the wheel polygons to develop to the higher-order polygons. Besides, high-order polygons will cause high-frequency vibration of the axle box, which is close to the natural frequency of the components surrounding it. Bolts and other parts of the axle box are susceptible to damage, posing a potential threat to the safe operation of the vehicle. To this end, the maximum value of the four types of surface damages (y_{11}, y_{12}, y_{13} and y_{14}) is selected as the overall surface damage state value in this model, as displayed in (20).

$$y_1 = \max(y_{11}, y_{12}, y_{13}, y_{14}) \tag{20}$$

where y_{11}, y_{12}, y_{13} and $y_{14}$are the values of peeling damage, scratching damage, grinding damage and polygon damage, respectively. y_{11}, y_{12}, y_{13} and y_{14} are defined as (21)-(24).

$$y_{11} = \begin{cases} 0, & PL = 0 \text{ } and \text{ } PD = 0 \\ 5, & 0 < PL < 40 \text{ } and \text{ } 0 < PD < 1 \\ 25, & PL \geq 40 \text{ } or \text{ } PD \geq 1 \end{cases} \tag{21}$$

$$y_{12} = \begin{cases} 0, & SD = 0 \\ 5, & 0 < SD < 0.7 \\ 25, & SD \geq 0.7 \end{cases} \tag{22}$$

$$y_{13} = \begin{cases} 0, & GW = 0 \\ 5, & 0 < GW < 5 \\ 25, & GW \geq 5 \end{cases} \tag{23}$$

$$y_{14} = \begin{cases} 0, & R = 0 \\ 5, & 0 < R < 0.6 \\ 25, & R \geq 0.6 \end{cases} \tag{24}$$

where PL and PD are peeling length and depth, respectively; SD is the scratch depth; GW is the grinding width, and R is the runout of wheels.

b: INTERNAL DAMAGE STATE MAGNITUDE

Wheel internal damage refers to the injury caused by rim crack and other derived cracks, which may cause severe accidents like collapse and derailing. Large particles of non-metallic inclusions, such as chain distributed Al_2O_3 spherical inclusions, are the essential reasons of rim crack initiation. The mechanism of the influence of inclusions on the rim crack generation is as follows: the difference of the thermodynamic properties, such as elastic modulus and thermal expansion coefficient, between inclusions and base metals means they have various thermal deformation rate and deformation degree. As a result, tensile stress will come into being at the junction. Then, under the influence of the tensile stress, inclusions and base metals will gradually separate and disengage from each other. At last, the inclusions are deformed, broken and fall off under the repeated action of the wheel-rail contact stress, hence cavities are formed at the original position of the inclusions. Cavities and falling inclusions are important factors leading to the crack initiation of the rim. As with the tread peeling damage, wheels with cracks can still be used after the crack is removed by re-profiling, but the depth of re-profiling is usually 3 to 12 mm, resulting in a great reduction in wheel life. The internal damage state magnitude model is displayed in (25).

$$y_2 = \begin{cases} 0, & ACC = 0 \text{ } and \text{ } DRC = 0 \\ 5, & 0 < ACC < 30 \text{ } and \text{ } 0 < DRC < 3 \\ 50, & ACC \geq 30 \text{ } or \text{ } DRC \geq 3, \text{ } reparable \text{ } crack \\ 100, & ACC \geq 30 \text{ } or \text{ } DRC \geq 3, \text{ } unreparable \text{ } crack \end{cases} \tag{25}$$

where ACC is the equivalent area of the circumferential crack, and DRC is the diameter of the radial crack.

c: FALLING BLOCKS DAMAGE STATE MAGNITUDE

Falling blocks is a phenomenon of crack initiation and metal spalling damage on the part or circumference of the tread due to thermo-mechanical action and/or wheel-rail contact fatigue during operation. Falling blocks often occur after crack propagation, mainly because of the presence of large chain inclusions in wheels. Once the falling blocks appear, the wheel dought to be scrapped as they pose intense threat to the stability and safety of the vehicle, which donates 0; otherwise, the wheel can be used normally, which donates 1. Thereupon, the falling blocks damage state magnitude model is as displayed in (26).

$$y_2 = \begin{cases} 0, & ACC = 0 \text{ } and \text{ } DRC = 0 \\ 5, & 0 < ACC < 30 \text{ } and \text{ } 0 < DRC < 3 \\ 50, & ACC \geq 30 \text{ } or \text{ } DRC \geq 3, \text{ } reparable \text{ } crack \\ 100, & ACC \geq 30 \text{ } or \text{ } DRC \geq 3, \text{ } unreparable \text{ } crack \end{cases} \tag{26}$$

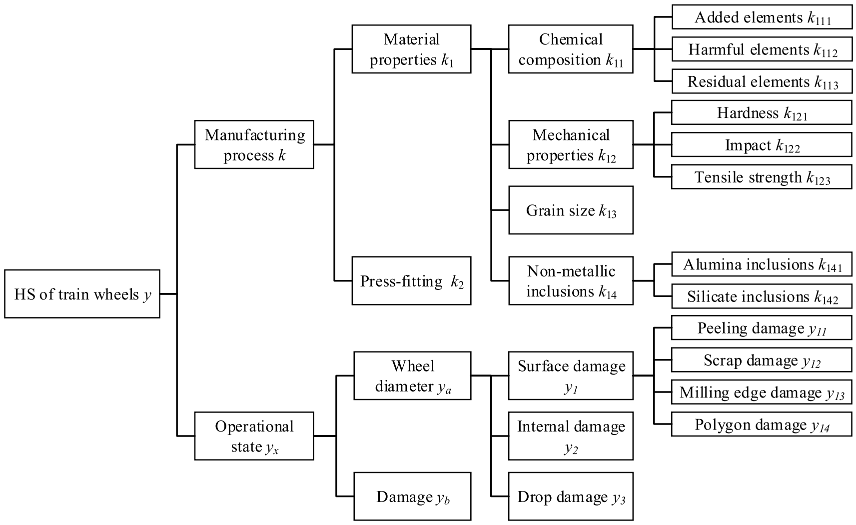

FIGURE 1. Evaluation indicators system of HS.

where b is a binary variable, if there is no drop damage, $b = 0$; otherwise, $b = 1$.

In summary, all the indicators used to calculate the HS of wheel are shown in Figure 1. According to the figure, the hierarchical relationships of the aforementioned indicators are presented clearly.

B. REMAINING USEFUL LIFE EVALUATION

The remaining useful life (RUL) of train wheels is affected by operational wear and re-profiling. Based on the general method in practical application, for wheels without surface damage and internal damage, the RUL can be calculated by (27).

$$S_1 = \frac{1250 - x - z}{1250 - x} \times \frac{x - 1150}{2b} \tag{27}$$

where S_1 is the RUL of wheel without damage, x is diameter of wheel, z is the accumulated diameter that has been lost in the past re-profiling, and b is the wear rate of tread of wheel.

For wheels with damage, the loss of diameters in re-profiling during the maintenance period should be considered. Thus, the RUL can be calculated by (28).

$$S_2 = \frac{1250 - x - z}{1250 - x} \times \frac{x - g - 1150}{2b} \tag{28}$$

where g donates the loss of diameters in the current re-profiling. Note that in the current stage, in order to ensure the operation safety of the train, the wheels installed on the train are replaced at regular time and mileage. In other words, the current maintenance strategy of the wheels is very conservative, which means that it is very difficult to find a wheel which has exhausted the RUL during the practical operation stage. Therefore, it is impossible to verify the RUL model under the actual operating environment. Nevertheless, a number of replaced wheels which finished their service will be further studied in the lab of CRRC Qingdao Sifang Locomotive & Rolling Stock Company Ltd. All the wheels will continuously work under the simulated environment until exhausting the RUL and related data will be collected to develop the RUL method. However, limited by the confidentiality provisions of the company, the experimental data can not be provided to the public. Therefore, we only present the RUL model in this study.

III. PHM APPLICATION

Based on the aforementioned health evaluation method, a system named PHM + Wheel is proposed. Figure 2. shows the conceptual diagram of the PHM + Wheel system.

In the system, the wheels are affixed with electronic tags containing a unique code before installation train. The entire data that covers the life span of wheels and corresponding tag codes are stored in the database to support the PHM of wheels.

After the manufacturing process, the material properties of wheels (e.g., physical properties, and inclusions et al.) are stored with a unique tag code. Then the fitting data (e.g., the magnitude of interference et al.) are stored after the press-fitting process. As a result, the fundamental database of wheels is constructed in the PHM + Wheel system.

During the operation, the data of each wheel are collected by the Chinese locomotive remote monitoring and diagnosis system (CMD) which has been widely implemented in the Chinese railway and wheel sensors. Meanwhile, considering that the automatic detection equipment service in the maintenance department can only obtain the vehicle code, the PHM + Wheel system connects the tag codes and vehicle codes, so that the detection results in the maintenance department can be related to each wheel and automatically stored in the database.

In the maintenance departments, the maintenance records are required to be stored in the maintenance database and related to the unique code of the wheels. To make the work

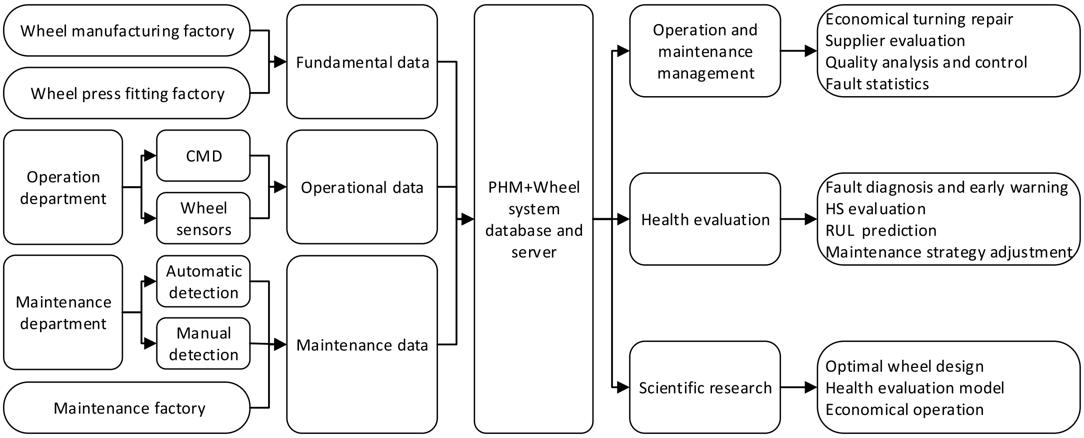

FIGURE 2. Conception diagram of the PHM + Wheel system.

TABLE 1. Description of the collected data of 44 wheels.

Factors	Mean	Standard deviation	Min	Max
Carbon/%	0.483	0.011	0.462	0.505
Silicon/%	0.317	0.024	0.281	0.374
Manganese/%	0.740	0.017	0.705	0.777
Sulfur /%	0.004	0.002	0.001	0.011
Phosphorus/%	0.011	0.003	0.004	0.015
Chromium/%	0.188	0.042	0.097	0.254
Nickel/%	0.100	0.058	0.022	0.230
Molybdenum/%	0.044	0.009	0.027	0.063
Tensile strength/MPa	890.638	20.405	416.377	854.25
Impact energy/J	24.568	2.204	4.856	20
Hardness/HBW	272.136	10.578	111.888	248
Grain size	7.727	0.788	0.622	6
Fine alumina inclusions	1.068	0.174	0.030	1
Coarse alumina inclusions	0.545	0.145	0.021	0.5
Fine silicate inclusions	1.057	0.161	0.026	1
Coarse silicate inclusions	0.568	0.174	0.030	0.5
Ratio of axle interference to wheel seat diameter/%	0.119	0.009	0.110	0.130
Wheel diameter/mm	1201.227	29.963	1157	1241
Peeling length/mm	0.909	4.214	0	20
Peeling depth/mm	0.027	0.128	0	0.7
Scratch depth/mm	0.018	0.121	0	0.8
Grinding width/mm	0.125	0.584	0	3.1
Runout/mm	0.059	0.222	0	1
Circumferential crack area/mm^2	0	0	0	0
Radial crack diameter/mm	0	0	0	0

more efficient and the decision-making results more accurate, portable equipment (e.g., personal digital assistants) is developed and equipped to the maintenance engineer, which allows for convenient updating of the manual detection data to the database and correcting the noise in the detection data.

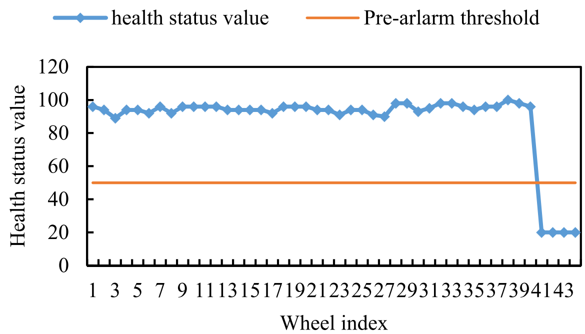

FIGURE 3. HS of 44 wheels.

FIGURE 4. Wheel under the pre-alarm status.

Based on the manufacturing data, operational data, and maintenance data, technologies including data cleaning, data fusion, data management [30], and health evaluation method proposed in this study are used to constructs the PHM + Wheel system. Then the system can provide practical decision-making support to the maintenance engineers for a smarter maintenance strategy. Furthermore, functions such as supplier evaluation, controlling quality and optimizing wheel design are also supported by the system.

IV. CASE HISTORY

The proposed PHM + Wheel system has made experiments in four railway administrations throughout China. To investigate

TABLE 2. Operational data of 44 wheels.

ID	Wheel diameter/mm	Peeling length/mm	Peeling depth/mm	Scratch depth/mm	Grinding width/mm	Runout/mm	Circumferential crack area/mm2	Radial crack diameter/mm	drop damage
1	1230	0	0	0	0	0	0	0	0
2	1231	0	0	0	0	0	0	0	0
3	1232	0	0	0	2.4	0	0	0	0
4	1231	0	0	0	0	0	0	0	0
5	1225	0	0	0	0	0	0	0	0
6	1234	0	0	0	0	0	0	0	0
7	1233	0	0	0	0	0	0	0	0
8	1234	0	0	0	0	0	0	0	0
9	1238	0	0	0	0	0	0	0	0
10	1237	0	0	0	0	0	0	0	0
11	1240	0	0	0	0	0	0	0	0
12	1241	0	0	0	0	0	0	0	0
13	1240	0	0	0	0	0.8	0	0	0
14	1240	0	0	0	0	0	0	0	0
15	1241	0	0	0	0	0	0	0	0
16	1241	0	0	0	0	0	0	0	0
17	1199	0	0	0	0	0	0	0	0
18	1200	0	0	0	0	0	0	0	0
19	1198	0	0	0	0	0	0	0	0
20	1198	0	0	0	0	0	0	0	0
21	1197	0	0	0	0	0	0	0	0
22	1196	0	0	0	0	0	0	0	0
23	1198	20	0.7	0	0	0	0	0	0
24	1198	0	0	0	0	0	0	0	0
25	1195	0	0	0	0	0	0	0	0
26	1195	0	0	0	0	1	0	0	0
27	1197	20	0.5	0	0	0.8	0	0	0
28	1196	0	0	0	0	0	0	0	0
29	1198	0	0	0	0	0	0	0	0
30	1197	0	0	0	3.1	0	0	0	0
31	1194	0	0	0.8	0	0	0	0	0
32	1193	0	0	0	0	0	0	0	0
33	1163	0	0	0	0	0	0	0	0
34	1162	0	0	0	0	0	0	0	0
35	1164	0	0	0	0	0	0	0	0
36	1164	0	0	0	0	0	0	0	0
37	1163	0	0	0	0	0	0	0	0
38	1164	0	0	0	0	0	0	0	0
39	1162	0	0	0	0	0	0	0	0
40	1161	0	0	0	0	0	0	0	0
41	1160	0	0	0	0	0	0	0	0
42	1159	0	0	0	0	0	0	0	0
43	1158	0	0	0	0	0	0	0	0
44	1157	0	0	0	0	0	0	0	0

TABLE 3. Manufacturing data of 44 wheels.

ID	Carbon/ %	Silicon/ %	Manganese/ %	Sulfur /%	Phosphorus /%	Chromium/ %	Nickel /%	Molybdenum/ %	Tensile strength/ MPa	Impact energy/J	Hardness /HBW	Grain size	Fine alumina inclusion	Coarse alumina inclusion	Fine silicate inclusion	Coarse silicate inclusion	Ratio of axle interference to wheel seat diameter/%
1	0.476	0.3	0.732	0.005	0.011	0.182	0.082	0.055	880.16	25	271	8	1	0.5	1	0.5	0.12
2	0.474	0.331	0.735	0.003	0.008	0.184	0.069	0.027	854.25	27	280	7	1	1	1	0.5	0.11
3	0.466	0.309	0.756	0.004	0.012	0.181	0.076	0.029	880.63	24	255	9	1.5	0.5	1	0.5	0.13
4	0.48	0.315	0.756	0.002	0.011	0.187	0.074	0.027	874.61	22	248	8	1	0.5	1	0.5	0.13
5	0.473	0.328	0.751	0.002	0.01	0.186	0.092	0.043	867.69	26	283	8	1	0.5	1.5	1	0.11
6	0.475	0.323	0.765	0.002	0.015	0.19	0.074	0.035	878.49	24	266	6	1	0.5	1	0.5	0.12
7	0.471	0.309	0.77	0.003	0.011	0.18	0.072	0.038	890.83	22	270	8	1.5	0.5	1.5	0.5	0.11
8	0.462	0.284	0.721	0.006	0.014	0.23	0.23	0.047	877.13	26	258	8	1	0.5	1	0.5	0.13
9	0.482	0.301	0.705	0.005	0.015	0.24	0.026	0.044	912.33	27	290	8	1	0.5	1	0.5	0.13
10	0.481	0.281	0.728	0.004	0.013	0.247	0.022	0.047	898.6	23	279	8	1	0.5	1	0.5	0.11
11	0.5	0.293	0.735	0.004	0.014	0.254	0.025	0.049	914.85	28	277	8	1	1	1	0.5	0.13
12	0.476	0.3	0.732	0.005	0.011	0.182	0.082	0.055	880.16	25	268	7	1	0.5	1	1	0.11
13	0.474	0.331	0.735	0.003	0.008	0.184	0.069	0.027	854.25	27	281	8	1	0.5	1	0.5	0.12
14	0.466	0.309	0.756	0.004	0.012	0.181	0.076	0.029	880.63	24	280	9	1	0.5	1	0.5	0.11
15	0.48	0.315	0.756	0.002	0.011	0.187	0.074	0.027	874.61	22	277	9	1	0.5	1	0.5	0.13
16	0.473	0.328	0.751	0.002	0.01	0.186	0.092	0.043	867.69	26	275	8	1	0.5	1	0.5	0.13
17	0.462	0.284	0.721	0.006	0.014	0.23	0.23	0.047	877.13	26	276	8	1	0.5	1	1	0.13
18	0.482	0.301	0.705	0.005	0.015	0.24	0.026	0.044	912.33	27	280	7	1	0.5	1.5	0.5	0.11
19	0.481	0.281	0.728	0.004	0.013	0.247	0.022	0.047	898.6	23	259	8	1	0.5	1	0.5	0.13
20	0.5	0.293	0.735	0.004	0.014	0.254	0.025	0.049	914.85	28	269	8	1.5	0.5	1.5	0.5	0.11
21	0.476	0.284	0.724	0.004	0.013	0.246	0.027	0.048	907.87	29	278	7	1	0.5	1	0.5	0.12
22	0.471	0.307	0.722	0.005	0.015	0.249	0.026	0.045	889.42	24	282	8	1	0.5	1	0.5	0.11
23	0.505	0.29	0.747	0.006	0.014	0.251	0.023	0.049	907.81	23	268	8	1	0.5	1	0.5	0.13
24	0.476	0.284	0.724	0.004	0.013	0.246	0.027	0.048	907.87	29	271	8	1	1	1	0.5	0.11
25	0.487	0.349	0.741	0.011	0.009	0.111	0.159	0.048	872.27	22	276	8	1	0.5	1	0.5	0.13
26	0.476	0.324	0.726	0.004	0.006	0.133	0.127	0.042	868.39	25	267	8	1	0.5	1	0.5	0.11
27	0.498	0.31	0.733	0.002	0.008	0.168	0.114	0.041	920.65	20	290	9	1	0.5	1	1	0.12
28	0.49	0.3	0.746	0.003	0.011	0.172	0.1	0.031	877.06	26	288	8	1	0.5	1	0.5	0.11
29	0.491	0.316	0.733	0.002	0.005	0.164	0.144	0.053	888.48	21	253	8	1.5	0.5	1	0.5	0.12
30	0.492	0.337	0.764	0.002	0.011	0.173	0.199	0.048	910.91	25	265	7	1	1	1	0.5	0.11
31	0.498	0.348	0.77	0.002	0.01	0.134	0.117	0.04	910.85	23	274	6	1	0.5	1.5	0.5	0.11
32	0.489	0.365	0.777	0.003	0.011	0.172	0.127	0.059	923.97	26	254	8	1	0.5	1	1	0.13
33	0.483	0.306	0.72	0.002	0.011	0.168	0.136	0.062	893.66	22	273	8	1.5	0.5	1	0.5	0.11
34	0.503	0.348	0.752	0.002	0.013	0.172	0.188	0.058	929.42	22	269	6	1	0.5	1	0.5	0.13
35	0.487	0.349	0.741	0.011	0.009	0.111	0.159	0.048	872.27	22	280	8	1.5	0.5	1	0.5	0.12
36	0.476	0.324	0.726	0.004	0.006	0.133	0.127	0.042	868.39	25	254	8	1	0.5	1	0.5	0.11
37	0.486	0.366	0.747	0.003	0.005	0.183	0.109	0.043	866.09	25	286	7	1	0.5	1	0.5	0.13
38	0.487	0.329	0.734	0.002	0.009	0.173	0.123	0.044	902.5	23	279	8	1	0.5	1	0.5	0.11
39	0.48	0.322	0.718	0.003	0.004	0.142	0.124	0.043	881.8	25	278	6	1	0.5	1	1	0.13
40	0.48	0.339	0.729	0.002	0.005	0.097	0.142	0.063	886.83	25	265	8	1	0.5	1	0.5	0.11
41	0.502	0.374	0.757	0.001	0.005	0.201	0.118	0.047	935.27	25	259	8	1	0.5	1	0.5	0.12
42	0.49	0.3	0.746	0.003	0.011	0.172	0.1	0.031	877.06	26	270	6	1	0.5	1	0.5	0.11
43	0.491	0.316	0.733	0.002	0.005	0.164	0.144	0.053	888.48	21	287	8	1	0.5	1	0.5	0.13
44	0.492	0.337	0.764	0.002	0.011	0.173	0.199	0.048	910.91	25	266	8	1	0.5	1	0.5	0.11

the feasibility of the PHM + Wheel system, a survey was conducted in July 2018 at maintenance departments of the Xian administration, where the PHM + Wheel system has been used for one year.

The maintenance records are checked and the engineers are interviewed to realize the effects of the PHM+Wheel system. The records show that no accidents were happened in the past one year after implementing the system, which demonstrates the feasibility and reliability of the PHM + Wheel system. According to the maintenance engineers, the workload is decreased and the work efficiency is increased for more than 25% and 5% respectively, thus positive comments are given by engineers for this system.

Furthermore, a field test was conducted to verify the system. 44 wheels with different characteristics from electronic locomotives HXD3020 (3C1), HXD372 (5C1), HXD30536 (3C2) and HXD3590 (4C1), which operates along the Xian-Ankang railway and Yangpingguan-Ankang railway, are selected as the samples. Each wheel has a unique code and corresponding condition data. The source of manufacturing data and operational state data are the manufacturer and maintenance department, respectively. The supporting data is displayed in Appendix and described in Table 1. After inputting the unique code of the wheels into the PHM+Wheel system, the system shows that 40 wheels under "fine" status and 4 wheels under "pre-alarm status". The health status values of 44 wheels are collected in the system and presented in Figure 3. Note that there is no wheel under the scrapped condition in the test due to the conservative maintenance strategy as discussed above. The evaluation results have been verified by maintenance engineers by manually investigating the status of wheels, which were concluded with high accuracy. Figure 4. presents a wheel with under the pre-alarm status, which shows that there exists scratch on the tread clearly.

During the survey, we found that the increase of efficiency is less than the decrease of workload. This can be explained that, due to the distinctiveness of railway industry, the safety is more important than cost or efficiency in practical application so that the maintenance engineers will take time to verify the evaluation results by system. On the other hand, although the portable equipment helps the updating of the maintenance records, it still occupies the time of engineers.

V. CONCLUSION

The purpose of this study is to propose a comprehensive and practical algorithm of train wheel health evaluation, which considers manufacturing process factors, operational factors and maintenance factors. This work contributes to existing knowledge of train wheel PHM by providing identifications of different wheel states (i.e., fine, attention, pre-alarm and scrapped). Additionally, the results derived from the proposed method are referred as supports for maintenance decision in PHM+Wheel system. Thus, it is expected to help reduce rolling stock wheel inspection and maintenance costs culminating to improve railway reliability.

However, the principal limitation of this study is that the model proposed is experience-based due to the lack of information on exact influence mechanisms of various factors. For example, an alternative method to evaluate the RUL is to establish the relationship between RUL and some related factors (e.g., diameter, physical properties). However, it is probematic since it will take a long time to accumulate enough data for investigating the factors effecting the RUL of train wheels at this current stage. A longer period application of the PHM+Wheel system is required to accumulate the data then develop a more advanced and smarter model. Meanwhile, the maintenance strategies of all kinds of equipment across the Chinese Railway system are being transformed from plan-based to condition-based. At the beginning of this transformation, PHM system has adequate functions, yet has not been constructed, resulting in a paucity of data and research findings. Notwithstanding these limitations, the PHM + Wheel system based on the proposed health evaluation method is expected to have unrivaled prospects and start a new beginning of intelligent railway and intelligent maintenance for the Chinese railway industry.

APPENDIX

The original data of 44 wheels are provided in this section. The Table 2 is the operational status data and the Table 3 is the manufacturing data.

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